REPORT NO. DCOCS-1

N64-17692 *

CODE-1

(NASA CR-55815;) OTS:

97p.

Prepared for:

NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON 1, TEXAS.

STUDY ON OPTICAL COMMUNICATIONS FROM DEEP SPACE

INTERIM PROGRESS REPORT

7 November 1962 through 7 January 1963

Kenneth L. Brinkman, 1963 97p rfs

AEROSPACE GROUP

HUGHES

1168202

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA

(NASA Contract ~~No.~~ NAS 9-879)
P. R. No. 3-440-20351
WAS 10-81-02-36

OTS PRICE

XEROX $ 8.60 ph

MICROFILM $ 3.11 mf.

INTRODUCTION

This Interim Progress Report presents a discussion of the work performed on Contract NAS 9-879 during the period from 7 November 1962 through 7 January 1963. Separate discussions of the activity in each of the give principal Work Task areas have been included. Major emphasis during this period was placed on completion of Task 1, the Microwave versus Optical Communication Systems Comparison. Other task areas, such as the Technological Studies and the Operations and System Analysis were executed in a manner which would permit timely contributions for the support of this effort. These contributions, as well as additional material, are also included.

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Project Manager
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COMMUNICATIONS STUDY

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1.0 MICROWAVE-VS-OPTICAL COMMUNICATION COMPARISON

For the purpose of comparing microwave and optical communication systems, the work organization flow chart shown in Figure 1.1 has been adopted. The left side of the chart shows the necessary preliminary inputs from the areas of Operations and Systems Analysis, Components Analysis, and Communication Theory. The tradeoff proper begins with a derivation of the fundamental range equations and in successive steps, reduces the number of parameters under consideration to essentially two: total spaceborne weight, and frequency. Considering the short time scale available, and the difficulty in obtaining reliable data over the enormous range of possible operating frequencies, it has been necessary to consider only 4 selected frequencies of transmission, 5 gc, 50 gc, 127 TC and 430 TC. The development ultimately gives a theoretical maximum bit rate per pound of payload weight at the selected frequencies. All parameters are then re-evaluated in light of expected future developments and the system performance figures are correspondingly upgraded, giving not only an estimate of future system capability, but some feel for which components are in critical need of improvement.

1.1 THE ELECTROMAGNETIC PROPAGATION RANGE EQUATION

The following paragraphs are concerned with the derivation of the familiar "range equation" for one way electromagnetic propagation between diffraction limited circular transmitting and receiving apertures. The transmission path is assumed to be loss-free.

The fraction of the transmitted power which is received will be equal to the ratio of the receiving antenna area to the cross sectional area of the transmitted beam at the receiver.

$$P_r = P_t \frac{A_r}{\pi (\theta_t R)^2}$$

P_r and P_t are the received and transmitted powers, respectively; A_r is the receiver aperture area, θ_t is the transmitted beam cone half angle, and R is the distance between transmitter and receiver. Using the appropriate expression for the diffraction limited beamwidth:

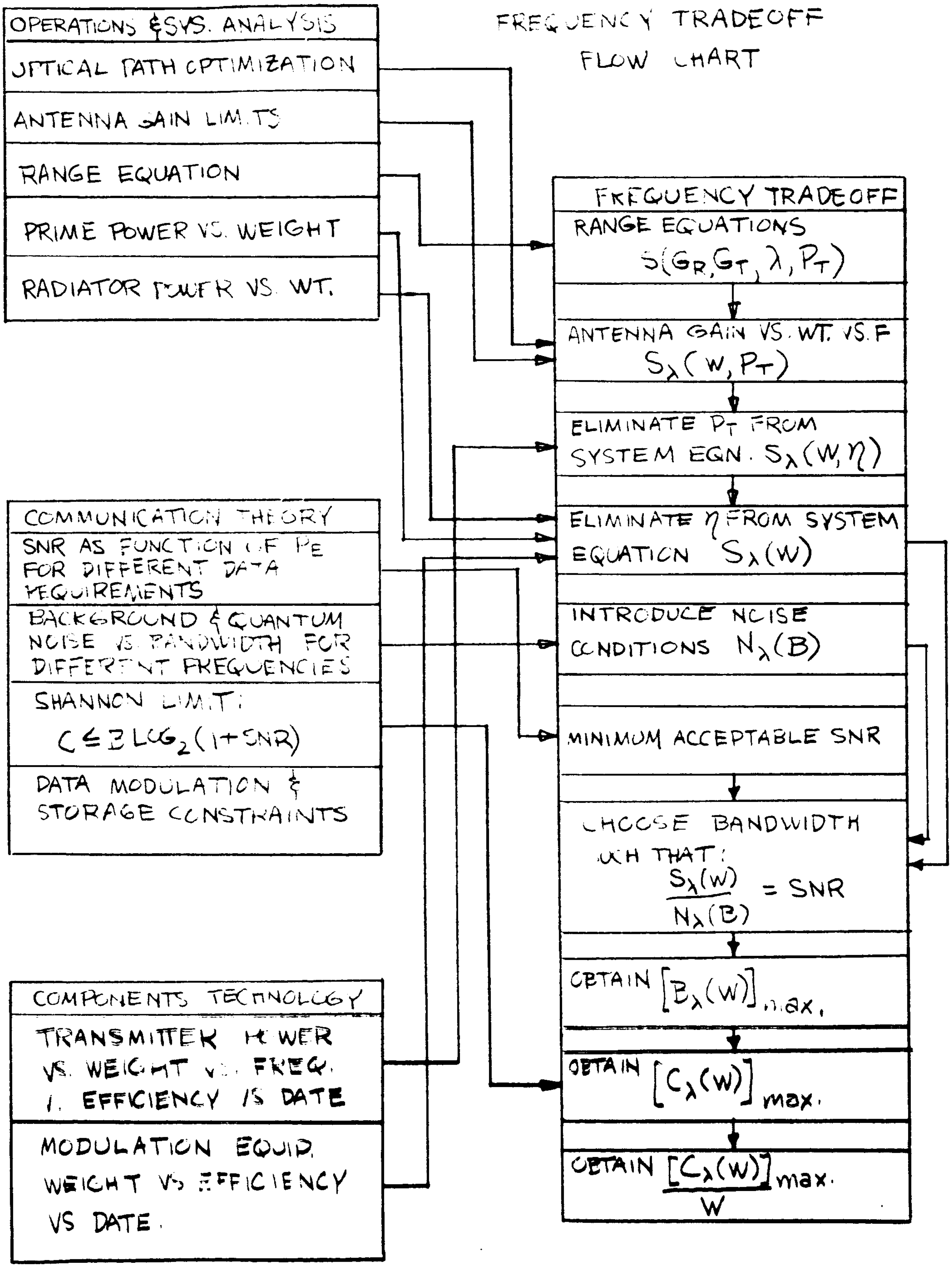
$$\theta_t = 1.22 \frac{\lambda}{d_t}$$

And the geometrical relationship:

$$A_t = \frac{\pi d_t^2}{4}$$

FIGURE 1.1

FREQUENCY TRADEOFF FLOW CHART



gives:

$$P_r = .212\, P_t \frac{A_r A_t}{\lambda^2 R^2}$$

where A_t is the transmitter aperture area, λ is the free space wavelength, and d_t is the diameter of the transmitter aperture.

The gain of a directive radiator is given by the ratio of the solid angle about a point to the solid angle of the directive beam. For a diffraction limited circular aperture this is given by:

$$G = 2.69 \frac{d^2}{\lambda^2}$$

In terms of the gains of the radiating elements, then:

$$P_r = \frac{P_t}{43} \frac{G_t G_r \lambda^2}{R^2}$$

Successive elements of this equation will be subjected to parametric analysis.

1.2 OPTICAL TRANSMISSION CONSIDERATIONS

Vital to the progress of any comparison of microwave and optical communication systems is a preliminary optimization of the possible optical transmission paths. The several path schemes are:

(1) Direct optical link between earth and deep space vehicle (DSV).

(2) Microwave link to artificial earth orbiting satellite and optical link from satellite to DSV.

(3) Microwave link to moon with optical link from moon to DSV.

The relative merits of each of these alternatives must be evaluated on the basis of the following criteria:

(1) Performance and state of the art in earth to earth satellite microwave communication.

(2) Optical antenna gain limitations for satellite and ground based stations.

(3) Atmospherics - refraction, dispersion, and absorption.

(4) Stabilization, pointing and tracking problems of ground based and satellite based optical antennas.

(5) Optical transmitter and receiver limitations for ground and satellite based equipment.

(6) Background noise environment for the earth and satellite based optical communication stations.

(7) Cost and coverage analysis of earth and satellite based optical stations.

Since the transmission of information from the earth to the deep space vehicle consists primarily of fairly leisurely commands and interrogations, it has been assumed that the limit of system performance will be more closely approached in the deep space vehicle to earth communication direction. Henceforth, only effects pertinent to information flow in this direction have been considered.

It is expected that, in view of the present capabilities of microwave communication between ground stations and earth orbiting satellites, very little system degradation can be introduced by the intermediate r.f. link. Microwave communication at lunar distances presents somewhat more of a problem, but in view of the anticipated performance of NASA operated DSIF equipment(1) (10^8 bits per second by early 1964), it appears as if the problems inherent to the inclusion of an intermediate microwave link may justifiably be neglected for purposes of the present tradeoff.

Optical antenna gain limitations due to atmospheric effects such as dispersive beam broadening and short term atmospheric diffraction fluctuations tend to shift the optimum optical transmission path in favor of a satellite based receiver station. Dispersion effects will typically broaden an optical antenna beamwidth to 10 microradians, while fluctuations in atmospheric diffraction at rates greater than 1 cycle per second typically occur at amplitudes of 25 microradians at zenith. The requirements on servo systems which will nullify the effects of this motion for large astronomical mirrors are great, hence one can infer a practical 25 microradian beam limit for an earth based optical station. This corresponds to a gain limitation of 103 db above isotropic. These effects are, of course, of negligible proportions in the lunar atmosphere and in the environment of an artificial earth-orbiting satellite.

Stabilization, pointing, and tracking accuracies of 0.1 to 1 microradian have been realized in large earth based astronomical mirrors. In view of the 25 microradian beam limit imposed on such devices, stabilization, pointing and tracking will not be a problem. Accuracies approaching the above mentioned limits apparently are not out of the question in artificial satellite applications - indeed 1 microradian accuracies have been proposed for the Orbiting Astronomical Observatory (OAO) Project. These accuracies impose a beam limitation on the orbiting mirror system which corresponds to a gain limitation of about 125 db, a number consistent with the use of a 30 inch diameter mirror aboard the orbiting vehicle. This size and weight appears compatible with present payload and component technology.

(1) "Radio and Optical Space Communications", Potter, Stevens and Wells. NASA contract NAS 7-100.

Optical transmitter and receiver capability as a function of weight and cost is an important input to this optical path optimization. A brief analysis shows that the performance of receiver factors such as detectors and demodulators, which are important to the transmission from DSV to earth, are not greatly enhanced by additional size and weight. While studies of this nature are continuing, for the present we have assumed that optical receiver performance is essentially the same for all geometrical configurations considered.

Results of a preliminary analysis of optical background effects at the distances of interest (included elsewhere in this report) show that in all cases except one, receivers are photon noise limited rather than background limited. This means that the received noise power is independent of receiver field of view. Thus no penalty is paid for using high gain receiver apertures, and background noise is not a factor in this tradeoff. The exception occurs when one attempts to receive through the daytime sky. This viewing condition imposes an additional restriction upon the earth based optical link, i.e., confinement to night time reception with an attendant increase in the number of stations and total cost for full coverage unless one were willing to accept the degradation due to daytime reception.

The results of a preliminary cost and coverage analysis for the considered optical paths is presented in Table 1.1. The first two entries refer to the use of a 24 hour synchronous communication satellite. Only one such station is needed for continuous reception and interrogation of the DSV, but equipment reliability figures could dictate the need for a second, redundant station. The quoted reliability figures refer to one commerical quality TV channel, whereas deep space probes would require only a reduced capability. Cost figures do not include optical equipment, but complete ground station cost is included. The second two entries refer to the use of more or less conventional large optical mirrors at ground locations. In order to provide the capability for continuous reception, desert locations were chosen over mountainous regions because of a lower occurrence of cloud cover. The estimates of ground station number must, in all fairness, be modified by a rigorous survey of long term weather conditions. This is being contemplated at present.

The somewhat conspicuous absence of any cost estimates on lunar based operations is due to the difficulty and expense of providing the required number of lunar stations and assuring their operational reliability.

Recourse to the above analysis shows that a net increase in received signal power may be realized by use of an optical link between DSV and earth satellite instead of a direct link between DSV and earth. This increase amounts to about 23 db for average atmospheric conditions, assuming 1.5 db degradation resulting from absorption of optical radiation by the earth's atmosphere. An effective power increase of this magnitude can be reflected in increased information transmission, lower DSV weight, and decreased DSV bulk. All this may evidently be accomplished at little or no cost increase.

TABLE 1.1

No. of Receivers	Equipment Reliability	Microwavelink Capacity	Coverage	Cost
1 (Synchronous)	97°/o	4 Commercial TV	100°/o	$12M (1)
2 (Synchronous)	99.9°/o	4 Commercial TV	100°/o	$22M
3 (Ground)	---	---	99°/o (2)	$7.5M (3)
6 (Ground)	---	---	99.99°/o (2)	$15M (3)

NOTES:

(1) Based on Advanced Project Syncom estimates.

(2) Based on estimated 4 cloudy days per year at selected desert locations.

(3) Based on average cost for a 100 inch parabolic mirror installation.

1.3 ANTENNA SYSTEM GAIN

The first of the parametric analyses to be performed in the overall optical versus microwave tradeoff concerns the spacecraft and ground-based antenna systems. Spacecraft antennas will be considered first.

The properties of spacecraft antennas for the frequency range 100 megacycles to 10 gigacycles are fairly well known and documented. Various curves have been presented relating gain to operating frequency with antenna weight as a parameter. One of these [1] forms the basis for the data presented in Figure 1.2. The results of antenna design studies of various construction techniques, which are valid over restricted frequency ranges, are presented in the same figure. Appendix A, at the end of this section, shows the derivation of these weight-gain-frequency relationships. Study of the curves shows that over the entire frequency spectrum, antenna gain per unit weight tends to increase somewhat more slowly than the inverse square of frequency. In spite of this, the possibility of overall gain enhancement at higher operating frequencies exists.

In order to realize any advantage from a ground based antenna system, a highly directive aperture must be considered. Practically, this means a parabolic reflector which may be said to be large in terms of wavelength units. Figure 1.3, which shows the gain variation with size (in wavelength units) has been reproduced from The Handbook of Astronautical Engineering. Typical fractional manufacturing tolerance for the microwave region has been shown as a parameter, although the curve is universally applicable for diffraction limited paraboloids. Optical tolerances can be much better than one part of 4000 if reasonable care is taken. In the practical limit, atmospheric effects will place an upper bound on the gains possible with a parabolic reflector. In support of the preceding statement, consider the following table which reflects present state of the art limitations of microwave paraboloid diameters.[2]

λ (cm)	D (ft) (Ground Based)
75	200
25	150
12	120
6	120
3	120
1.5	100

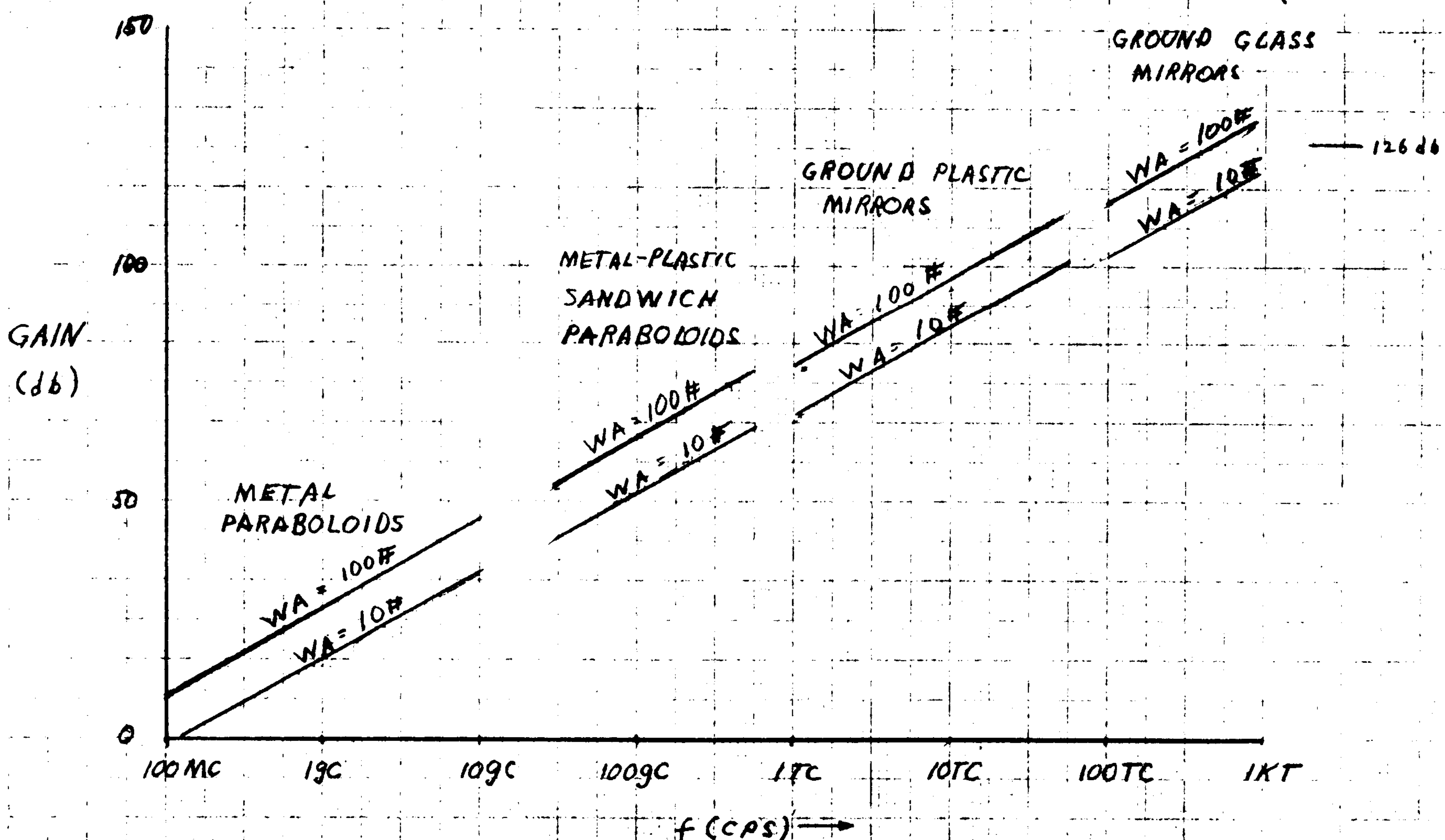
---

(1) G.E. Mueller, "A Pragmatic Approach to Space Communication", Proc. IRE, April 1960, page 559.

(2) IRE Transactions on Military Electronics. 1961 page 330.

FIG. 1.2

PARABOLIC ANTENNA GAIN vs FREQUENCY
FOR DIFFERENT CONTRUCTION TECHNIQUES



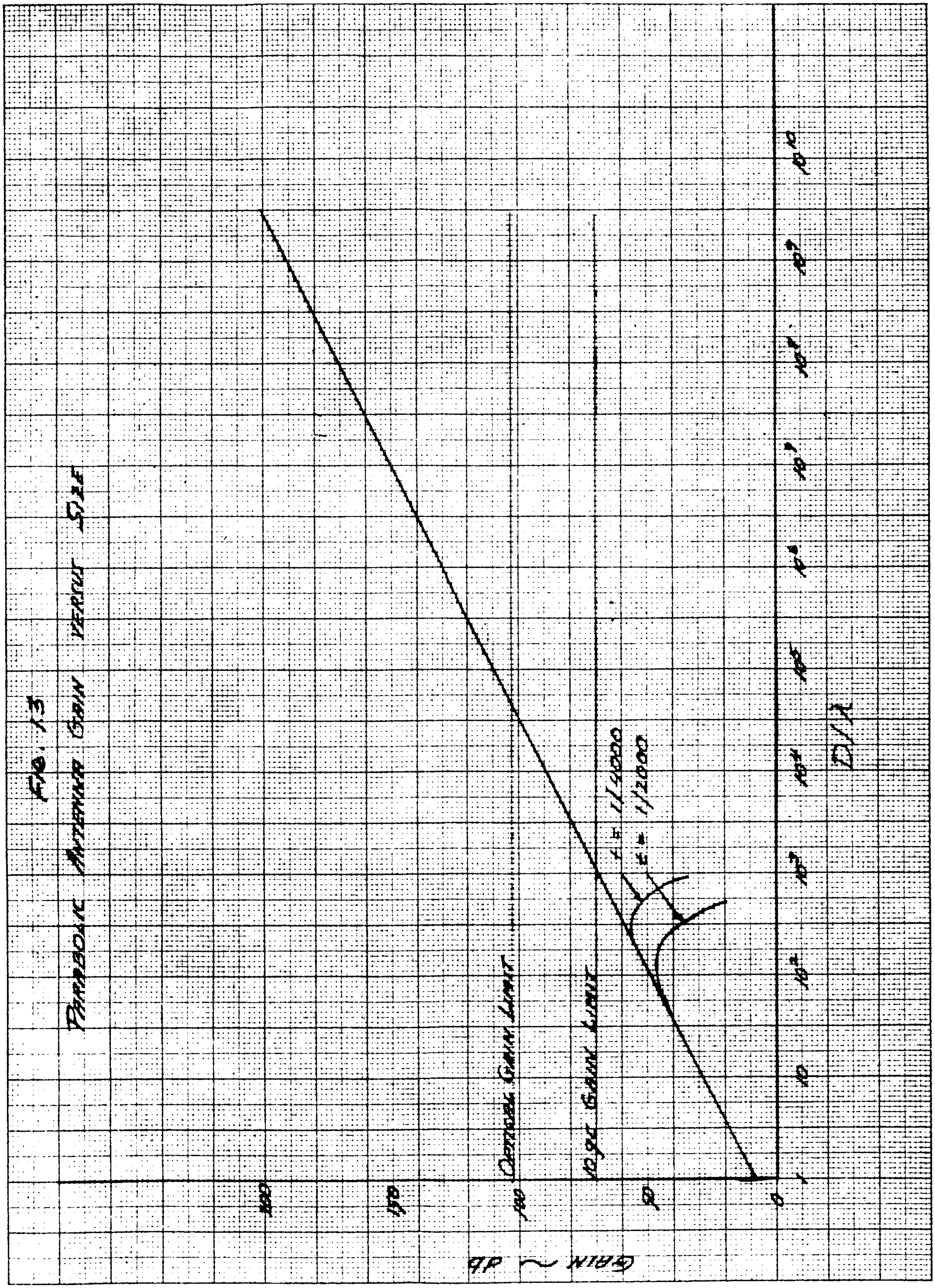


FIG. 13
PARABOLIC ANTENNA GAIN VERSUS SIZE
OPTICAL GAIN LIMIT
10 GC GAIN LIMIT
ε = 1/4000
ε = 1/2000
GAIN ~ dB
0
50
100
150
200
D/λ
1
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}

These gain limits are frequency sensitive and have been calculated as 70db for radiation at 10 gigacycles and about 103 db at a representative optical frequency. (7000 A). Scanty information at intermediate frequencies prohibits calculation of gain limits at frequencies other than these. Until the advent of more sophisticated reflector orienting servos, we must evidently live with these limitations for ground based receivers.

1.4 TRANSMITTED POWER

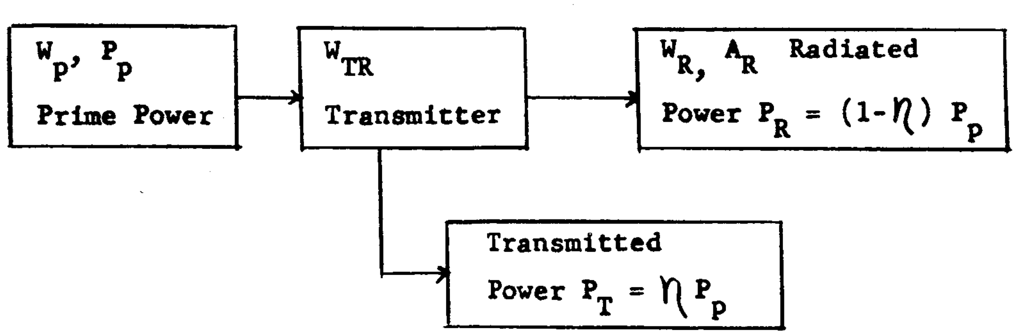
Extensive literature surveys presented elsewhere in this report bring to light a great deal of information on the present power capability of optical carrier generators. In addition, the art of carrier generation at radar frequencies is well documented. A brief, definitive summary is presented in Figure 1.4. Unfortunately, laser experimenters have only superficially reported the conversion efficiencies and weights of their devices. Representative values for the ruby and $CaF_2:D_y^{++}$ lasers are as follows:

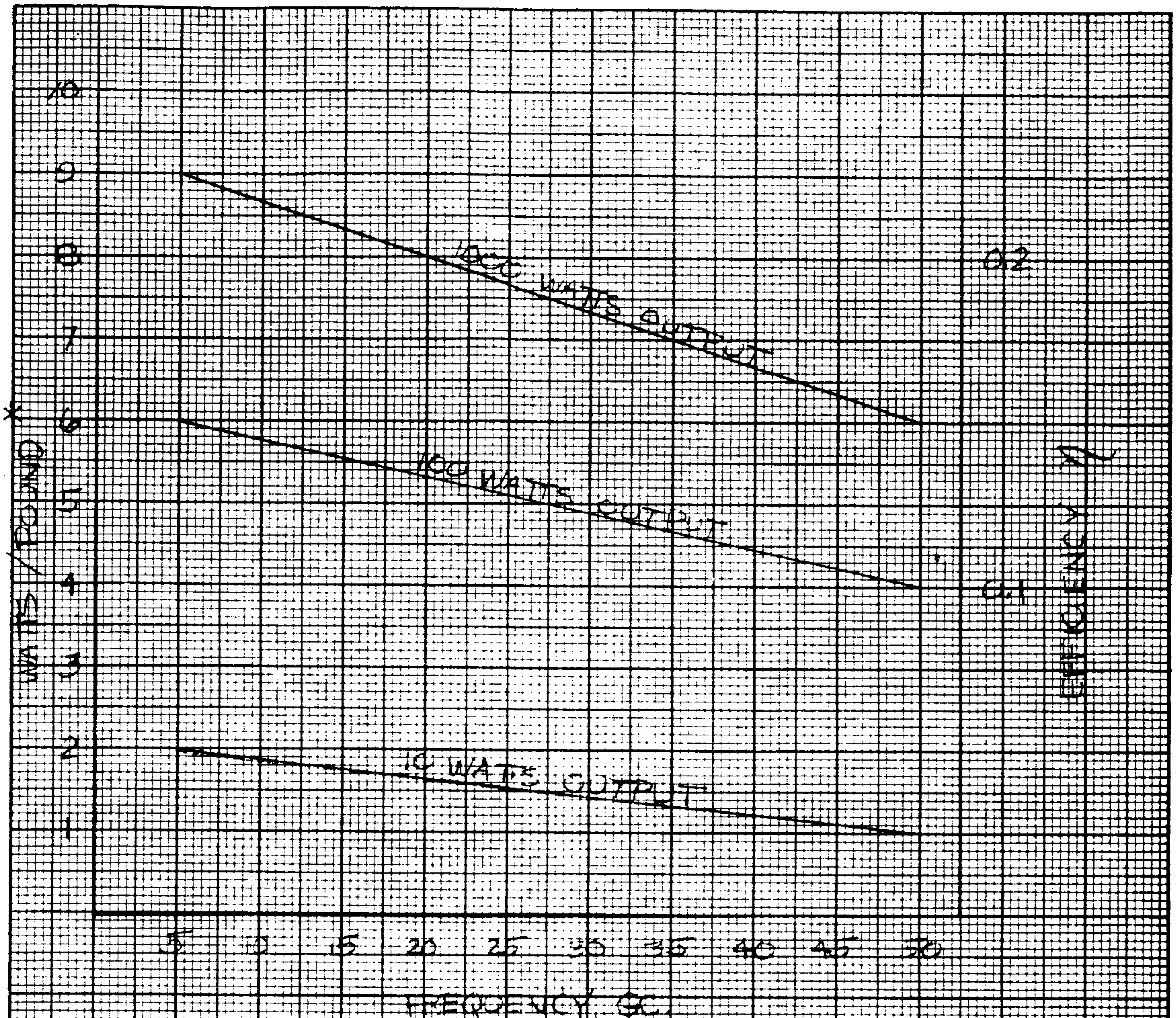
Type	λ	η	Mode	Weight*	Power
$CaF_2:D_y^{++}$	2.36μ	.01	CW	5 lb	1 watt
Ruby	$.69\mu$	.01	CW	5 lb	1 watt
Ruby	$.69\mu$	.01	Pulsed	5 lb	3 K watts

* Excluding prime power supply and energy storage devices.

1.5 TRANSMITTER PACKAGE WEIGHT

A knowledge of transmitter efficiency, output power and weight allows the derivation of a relationship between total transmitter package weight (including cooling surfaces and prime power supply) and efficiency. The following block diagram depicts the power flow within the prime power-transmitter-cooling surface system and shows associated subsystem weights.





* EXCLUDING PRIMARY POWER SUPPLY AND
FM OR PM ASSUMED

FIG. 14 ESTIMATED TRANSMITTER
EFFICIENCIES IN SPACE
SYSTEM APPLICATIONS

According to the Stefan-Boltzman radiation law, the amount of radiated power from a surface of area A_R, form factor f and temperature T is given by:

$$P_R = A_R f\sigma T^4$$

We will assume a form factor of .5, which is very slightly optimistic, and a value for the Stefan-Boltzman constant of 5.12×10^{-9} w/ft^2 $^oK^4$. Re-arranging terms, we obtain :

$$A_R = \frac{P_R}{.5\sigma T^4} = \frac{(1-\eta)P_p}{.5\ \sigma T^4} = \frac{\left[\frac{1-\eta}{\eta}\right] P_T}{.5\sigma T^4}$$

This relationship shows that a considerable reduction in radiative surface may be gained by operating the surface at high absolute temperature. We must assume, however, that environmental limitations on our equipment prohibits great excursions from a temperature of 300°K. This assumption gives, in a sense, a worst case estimate of radiative surface weight. In addition, the systems and operations analysis portion of this report presents an average value of 9 pounds of weight penalty per square foot of radiative surface. We obtain, for the total weight of radiative surface:

$$W_R = 9A_R = \frac{9\left[\frac{1-\eta}{\eta}\right] P_T}{.5\sigma\ (300)^4} = .435 \left[\frac{1}{\eta} - 1\right] P_T \text{ lbs.}$$

The weight of the prime power supply can be given by:

$$W_p = DP_p = D\frac{P_T}{\eta}$$

where D is an inverse power density, typically 0.1 pounds per watt for the case of solar cell prime power. The total weight of prime power supply and radiator is typically:

$$W_T = W_p + W_R = .1\frac{P_T}{\eta} + .435\ P_T \left[\frac{1}{\eta} - 1\right]$$

Re-arranging terms:

$$\frac{W_T}{P_T} = \frac{1}{\eta}(.535) - .435$$

This relationship is plotted in Figure 1.5 and is used as a basis for deriving weights associated with a particular transmitted power and conversion efficiency. In the event that modulator power requirements become a significant portion of transmitted power, Figure 1.5 may also be used to calculate weights associated with prime power and cooling of the modulator.

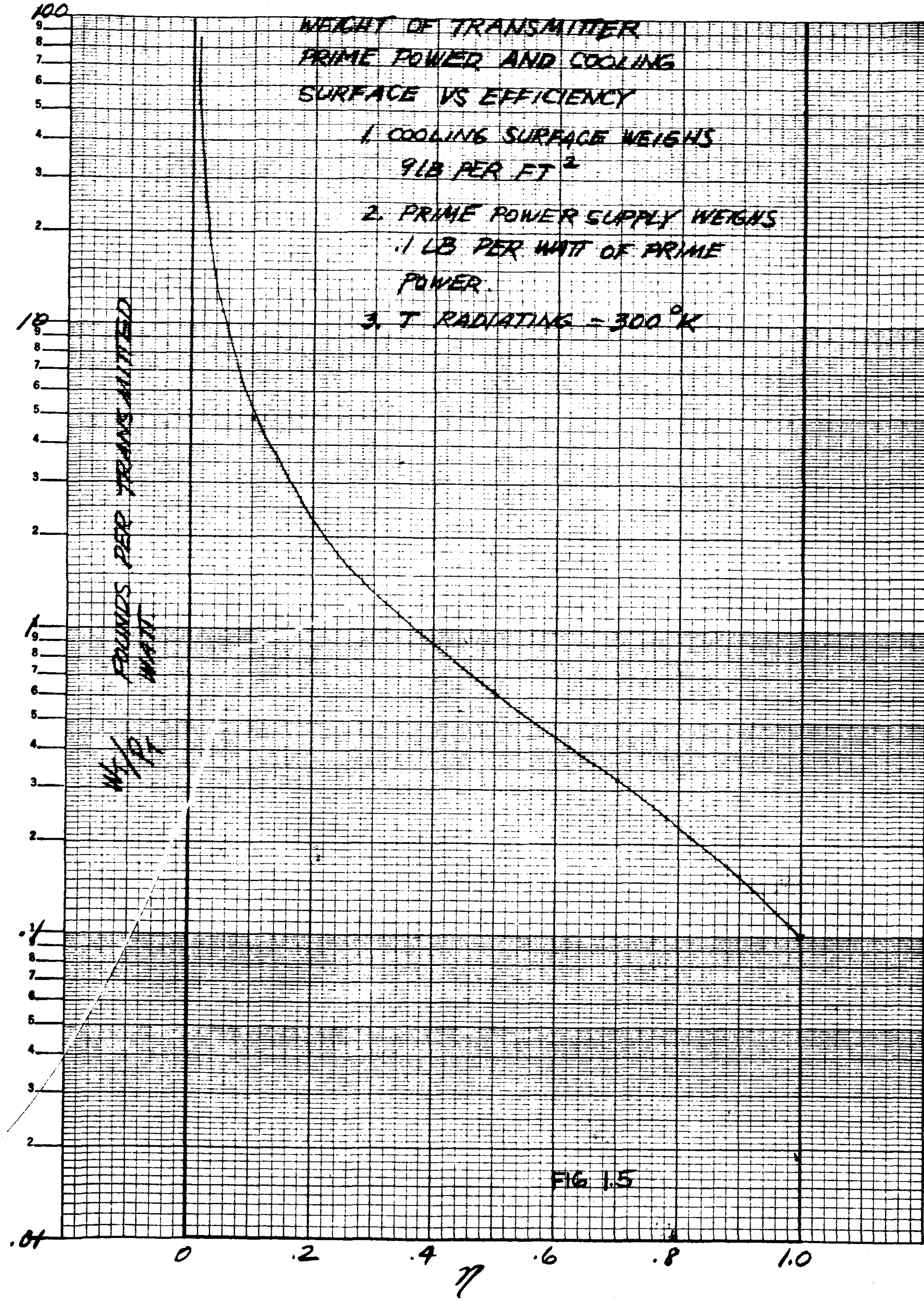

WEIGHT OF TRANSMITTER
PRIME POWER AND COOLING
SURFACE VS EFFICIENCY
1. COOLING SURFACE WEIGHS
9 LB PER FT^2
2. PRIME POWER SUPPLY WEIGHS
.1 LB PER WATT OF PRIME
POWER.
3. T RADIATING = 300°K
W_T/P_T
POUNDS PER TRANSMITTED WATT
100
10
1
.1
.01
0
.2
.4
.6
.8
1.0
η

FIG 1.5

1.6 COMMUNICATION AND INFORMATION THEORY CONSIDERATIONS

Starting with the estimates of minimum acceptable error rate for different modes of data transmission presented elsewhere in this report, and assuming the error rate to be given by:

$$P_e \simeq \frac{1}{2} e^{-SNR}$$

one may define a minimum acceptable signal to noise ratio (SNR). A typical error rate requirement of 10^{-5} gives a minimum SNR of about 10 db. The expression relating error rate to SNR is actually strictly valid only in the presence of White-Gaussian noise. While this assumption is clearly valid at microwave frequencies, it is not necessarily true in the presence of quantum noise. Best present estimates indicate that the relationship is not far from correct.

This problem is discussed in somewhat greater detail in the Optical Detection Section of this report, and will be a subject of continuing study for the following study phase.

1.7 SYSTEM NOISE

Pertinent results of background and quantum noise studies conducted under the Systems Considerations portion of this report are summarized in Figure 2-18, which shows the sum of photon noise and background noise as a function of channel bandwidth for selected frequencies. This tradeoff will consistently assume that optical detector noise is insignificant compared to quantum noise.

1.8 INSERTION OF SALIENT PARAMETERS

Previous sections of this microwave versus optical frequency tradeoff have been concerned with developing techniques for the selection of representative system parameters and with summarizing the results of other sections of the overall report which are pertinent to this tradeoff. A calculation of communication system performance factors for a typical frequency follows.

Beginning with Figure 1.4 and choosing a 5 gc frequency, one obtains typically, 100 watts of transmitted power at an efficiency of .15 and a total weight of 16.7 pounds. Recourse to Figure 1.5 gives a ratio of W_T to P_T of 3.3 for $\eta = .15$. Here W_T is the weight of prime power supply and thermal radiator, and P_T is transmitted power. Multiplication of W_T/P_T by P_T gives $W_T = 330$ pounds, which, when added to the weight of the transmitter itself, gives the total weight of the transmitter system, namely 347 pounds. At microwave frequencies, the modulator weight has been assumed to be a small part of the transmitter system weight; hence, modulator weights are included in the data of Figure 1.4. The best proposed optical beam modulators consume 10 watts average at gigacycle rates, hence modulator weight must be considered in the optical system. This may also be calculated from Figure 1.5 assuming gigacycle rate modulator power may be supplied by a commercial 2.5 pound 25°/o efficient, 10 watt CW traveling wave tube.

Selection of a transmitting and receiving antenna for our 5 gc system is done according to Figures 1.2 and 1.3, respectively. A 10 pound spacecraft antenna gives a gain of 32 db, while the ground antenna is practically limited to 60 db gain. This choice boosts total spaceborne equipment weight to 357 pounds.

The fundamental range equation may now be used to calculate received signal strength in db relative to one watt. Reducing such factors as $\frac{\lambda^2}{R^2}$, $\frac{1}{43}$ and P_T to db units, one obtains the received signal strength entered in Table 1.3.

The assumption of a maximum permissible error rate of 10^{-3} and a minimum SNR of 10 db means one may accept a maximum noise power N_r of $P_r/10$.

Figure 2-18 gives the relationship between noise power and bandwidth at the receiver. A noise power N_r of -154 dbw allows a maximum bandwidth B_r of 1.2 MC at the receiver.

Use of the Shannon limit

$$C\ \text{max.} = B_r \log_2 (1 + SNR)$$

gives a maximum bit rate of 1.2×10^4 bits per second per pound of transmitter plus antenna system weight.

Similar calculations are summarized in Tables 1.2 and 1.3 for other frequencies and dates.

1.9 LIMITATIONS OF TRADEOFF STUDY

It is wise at this point to regress for a moment and discuss some of the assumptions made in compiling Table 1.3.

The particular frequencies present were chosen strictly on the basis of amount of available data.

The optical portion of the table assumes propagation between the DSV and a synchronous communication satellite while the microwave portion considers a direct DSV to earth link.

A tacit assumption that microwave state of the art will not change significantly during the time scale considered in Table 1.3 has been made - indeed a great number of the assumptions relating to microwave technology are based on somewhat optimistic calculations.

TABLE 1.2

TRANSMITTER, PRIME POWER, AND COOLING
WEIGHT AT SELECT FREQUENCIES

Frequency	P_T (Watts)	η	Wxmtr (Lb)	W_T/P_T	W_T (Lb)	W_T + Wxmtr
5 gc	10	.05	5	11	110	115
5 gc	100	.15	16.7	3.3	330	347
5 gc	1000	.225	111	1.9	1900	2010
50 gc	10	.025	10	20	200	210
50 gc	100	.10	25	4.9	490	515
50 gc	1000	.15	167	3.3	330	3470
430 TC	1	.01	5	53.1	53.1	58.1
430 TC	10*	.10*	5	4.9	49	54
430 TC	3 KW (pulsed .001 duty)	.01	5	53.1	159	164
127 TC	1	.01	5	53.1	53.1	58.1
127 TC	5*	.10*	5	4.9	24.5	29.5
2 gc (Modulator)	10	.25	3	1.7	17	20

* Future date - 1966

Spacecraft antenna weight has been arbitrarily held low; the ten pound figure seems consistent with stabilization inaccuracies, although the figure of 115 db used as a maximum spacecraft optical antenna gain limit implies stabilization errors of 2.25 μ rad. instead of the proposed OAO upper limit of 1 μ rad.

Use of solar cells for prime power and the mere dumping of waste heat into space are quite arbitrary. Total power requirements can and do affect the choice of a proper power supply, while low efficiency transmitter devices might make use of a scheme to convert waste heat into prime power. This optimization has not been considered.

Finally, the absence of receiver parameters restricts the comparison to one of channel capacity and not overall data transmission. Demodulation and detection are under further study, and the results will be introduced at a further date.

1.10 DISCUSSION OF TRADEOFF RESULTS

The CW systems tabulated in Table 1.3 have a present theoretical bandwith capability of 1.2 megacycles in the microwave region and 3 megacycles in the optical. In view of the fantastic information carrying capacities claimed for coherent light sources, these figures sound a bit discouraging; but such a reaction is unwarranted. Consider, for instance, the maximum bit rate per pound of transmitter system weight. These results show a clear five-fold advantage for the CW optical system, with the additional advantage of allowing reduced total system weight and bulk - certain vehicle payloads may dictate the use of minimum weight communications configurations.

Present techniques will allow the use of the ruby crystal laser in the pulsed-feedback mode described in the modulation section of this report. For a system weight of 200 pounds, this configuration gives maximum bandwidths of the order of 10 gc. and maximum information rates of about 10^8 bps per pound. Comparison of these figures with those for representative CW operation is misleading since a data storage readout problem exists. This limitation is discussed elsewhere in this report. In addition, the tabulated bit rate must be modified by the duty cycle (presently 10^{-3}, but going up).

Expected future improvements include higher output power levels for CW optical devices, higher pulse repetition rates, and a general optical device efficiency upgrading. Future optical systems will enjoy an even greater advantage over microwave systems in the areas of weight, bandwidth, and information rate per unit weight.

TABLE 1.3

COMMUNICATION SYSTEM CAPABILITY

RANGE = 6×10^{10} METERS

Parameter	5 gc	50 gc	2.36µ	2.36µ	.69µ	Pulsed .69µ	2.36µ	2.36µ	.69µ
G_R (db)	60	60	105	115	115	115	105	115	115
G_T (db)	32	48	105	115	115	115	105	115	115
W_a (Lb)	10	10	10	100	10	10	10	100	10
λ^2 (M^2)	3.6×10^{-3}	3.6×10^{-5}	5.6×10^{-12}	5.6×10^{-12}	4.9×10^{-13}	4.9×10^{-13}	5.6×10^{-12}	5.6×10^{-12}	4.9×10^{-13}
P_T (dbw)	20	20	0	0	0	+35	+7	+7	+10
Wtrans (lb)	347	515	80	80	80	186	51.5	51.5	76
Wtotal (lb)	357	525	90	180	90	196	61.5	152	86
λ^2/R^2 (db)	-240	-260	-328	-328	-339	-339	-328	-328	-339
1/43 (db)	-16.3	-16.3	-16.3	-16.3	-16.3	-16.3	-16.3	-16.3	-16.3
P_R (dbw)	-144	-148	-134	-114	-125	-90	-127	-107	-115
$N_R = P_R/10$ (dbw)	-154	-158	-144	-124	-135	-100	-137	-117	-125
Bmax (cps)	1.2M	200K	30K	3M	40K	2×10^{10}	500K	30M	1.8M
C max $\left(\frac{\text{bits}}{\text{lb sec}}\right)$	1.2×10^4	1.3×10^3	1.2×10^3	5.5×10^4	1.6×10^3	3.5×10^8	2.7×10^4	6.5×10^5	7.3×10^4
Date	1963	1963	1963	1963	1963	1963	1966	1966	1966

APPENDIX A

DERIVATION OF SPACECRAFT ANTENNA SYSTEM GAIN AS A FUNCTION OF WEIGHT AND FREQUENCY

(1) Optical quality ground glass mirrors:

The following assumptions have been made:

(a) Coefficient of thermal expansion $C_T = 3 \times 10^{-6}$ per $^{\circ}K$. (Pyrex)

(b) Point to point maximum mirror surface temperature variation $\Delta T = \pm .5^{\circ}K$ (Thermal control required.)

(c) Mirror weight increases as square of aperture diameter due to extensive honey combing.

(d) Allowable surface deviation $\Delta = \lambda/16$

(e) Pyrex density D = 200 lb/ft.^{3}

(f) Diffraction limited gain increases as square of aperture diameter.

The weight of a reasonable size optical mirror may be expressed as:

$$W = \frac{\pi}{4} d^2 \times \frac{d}{16} D$$

A six inch diameter pyrex mirror weighs 2.5 lb., typically.

The gain of a parabolic, diffraction limited reflector is given by:

$$G = \frac{4\pi}{(1.22)^2} \left(\frac{d}{\lambda}\right)^2$$

A six inch diameter mirror gives a gain of about 110 db at a frequency corresponding to a wavelength of 7000 a.

From these relationships and assumptions the following table is derived:

d	W	0 1/2 Beam	Gain (λ=7000A)
6"	2.5 lb	6 μ rad.	110 db
12"	10	3	116
18"	25	2	120

Environmental effects will set a maximum limit on the usable frequency range of a given mirror. Let D_T represent a dimension critical to optical mirror performance (say the focal point to surface distance). The maximum variation of D_T has been shown by several sources to be equal to $\lambda/16$. Using the relationship:

$$\Delta = \frac{\lambda \text{ min.}}{16} = C_T \, D_T \quad T$$

one may derive the minimum usable wavelength of a 6 inch mirror as 6900 Angstroms. Larger mirrors naturally have larger values of λ min. Eventually, optical mirror environmental problems will have to be investigated more fully.

(2) Silvered-ground plastic mirrors for operation in the neighborhood of 10 terracycles:

The sort of assumptions as to the gain and weight variations with aperture diameter as were made for ground glass mirrors are applicable here. It is only necessary to tie down one point on the gain vs. frequency curve for purposes of a rather crude estimate. The following parameters are not unreasonable:

(a) Density of plastic 70 lb/ft^2

(b) Diameter of reflector = 1 meter.

(c) Surface tolerance = $\lambda/16$ = .0002 cm.
(f=10TC)

This particular configuration gives a gain of about 92 db and weighs around 50 pounds.

(3) Plastic - metal sandwich construction for operation at 20 to 150 gigacycles:

Antennas for a 50 gc frequency which have the following values may be fabricated using this construction technique:

(a) Diameter = 1 meter.

(b) Weight = 10 pounds.

(c) Gain = 48 db.

2.0 OPERATIONS AND SYSTEMS ANALYSIS

The selection of a system or systems for communication over millions of miles will be strongly influenced by the mission and the operational aspects of the tasks to be performed by the space vehicles. In order to optimize the design of the communication system in any worthwhile sense, it will be necessary to perform an operations analysis of the mission and a systems analysis of the general communication system, to evolve a model from which useful parameters may be deduced and parametric limits and ranges determined.

2.1 COMMUNICATION SYSTEM REQUIREMENTS

The nature of the various feasible and probable missions must be determined and the communication systems requirements specified by a set of communications requirement "profiles". These profiles will give message duration and fidelity, information rate, and other essential data as a function of mission phase, duration, type, location, etc. Relative priorities of messages and allowable or requisite flexibility must be considered.

Types of Data

A space communication system will be concerned with the transmission of three major types of data:

1) Speech - general voice communication

2) Scientific and engineering - spacecraft system sensors, guidance data, etc.

3) Pictures and television - real time television, facsimile

The systems requirements of the communication link will be dependent on the data requirements of the three classes of data. Of prime importance in specifying a link and assessing its capabilities will be the determination of the data requirements criteria. In particular, the following data requirements must be determined:

1) Speech

   Acceptable bandwidth
   Acceptable transmission errors

2) Scientific and engineering

   Information rate profile
   Data correlation
   Acceptable transmission errors

3) Pictures and television

Resolution
Frame rate
Element quantitization
Types of scenes or pictures
Acceptable transmission errors

The determination of these data requirements is largely subjective, but reasonable estimates can be given based on present communication practice. Table 2-1 illustrates typical data requirements for common classes of data.

It is not obvious that there would be any justifiable requirement for real-time communication of speech, data, or pictures in deep space missions. Since the transit time for an electromagnetic wave will characteristically be many minutes it is difficult to see why a further delay would be of any consequence in most missions. Although vehicular and planetary speeds in space are large, the spaces to be traveled are so enormous that the times are great and for most missions any decisions or information flows are not of an immediate nature. Plenty of time will be available for consideration, computation and transmission. There are cases involving observation of transient phenomenon where the data must be gathered quickly, but except where the space vehicle itself is in immediate danger of destruction this data can be stored for later transmission at a less-than-real-time rate. In the case of communication with a station based on a rotating moon or planet, or on a satellite which is periodically obscured it may be desirable to transmit a given quantity of stored data in some relatively small fixed time, say 12 hours for the Earth, on 1.5 hours for the less likely case of a 100 mile high Earth Satellite. Some indication of the total information rates for scientific data can be had from the Mariner II, which transmitted 720,000 data bits per day from 7 scientific instruments during inter planetary flight. About 150 data bits were used for each scientific data point.

By the time manned deep space flight arrives most of the basic information about inter planetary space will be known. Although there will always be requirements for experiments in space and of increasing sophistication, early manned flights will undoubtedly not have this requirement, and most communication will be monitoring of spacecraft performance, with large increases near end points of flight, planets, moons, etc.

Source-Destination Relationships

Telemetry to earth satelites and moon probes -- "short-range" space vehicles -- has already reached an adequate stage of development, if not optimized. Attention will therefore be focused on longer than lunar missions. An attempt is made here to classify them briefly and outline some principal parameter values.

Several categories are possible. The known solar system is comprised of 1 star, 9 planets, 31 moons or natural satellites, over 1500

TABLE 2-1

Some Possible Space Missions, Minimum Energy Transfers (Hohmann Ellipses)

1	2	3	4	5	6	7	8	9
Sun	OW RT	P		93	8.3	93	8.3	
Mercury	OW RT	P	0.76	57	5.1	133	11.9	3330
Venus	OW RT	P P or M	0.38 2	26	2.33	160	14.3	8760
Mars	OW RT	P P or M	0 68 2.66	50	4 48	234	21.0	11650
Martian Moons	OW RT	P P or M	2.66	50	4.48	234	21.0	11650
Jupiter	OW	P	2.8	392	35.1	576	51.7	

Column Headings:

(1) Destination, from Earth

(2) One way or round trip

(3) Probe or manned flight

(4) Minimum energy trip time from Earth, years

(5) Minimum maximum distance from Earth, 10^6 miles

(6) Time for transit of light signal, seconds

(7) Maximum distance from Earth, 10^6 miles.

(8) Time for transit of light signal maximum distance, seconds.

(9) Weight in pounds per man for food, air, water, at 12 lbs. per man per day.

TABLE 2-2 TYPICAL DATA REQUIREMENTS

Type	Signal Bandwidth	PCM Representation, bits/sample	Maximum Bit Rate	Tolerable Error Rate
Scientific data	0-1 kc	9	18 kilobits	10^{-2}
Engineering data	0-1 kc	7	14 kilobits	10^{-2}
Command data			50 bits	10^{-5}
Teletype			75 bits	10^{-5}
Speech	0-4 kc	5	40 kilobits	10^{-3}
Real time television (500x500 element picture)	15 cps-4mc	6	48 millibits	10^{-3}
Pictorial transmission (500x500 element picture in 12.5 seconds)	15 cps-10 kc	6	120 kilobits	10^{-3}

asteroids and comets, meteors, dust. etc. Except for Pluto, the planets are all very nearly in a plane and in near-circular orbits that revolve around the sun counterclockwise as seen from above the north pole. Most of the moon orbits are considerably inclined to the ecliptic. The planets range from 0.3 to 30 astronomical units from the sun, and the moons range from 2.54 to 332 planet radii from their planets. Since the Milky Way, the earth's galaxy, is inclined at about 62 degrees to the celestial equator, certain space missions conceivably would never look into it as a background. Most vehicles, however, will view the earth or other communication stations against the Milky Way as a background at least during a portion of the mission.

Since it is not possible to foresee or to prepare now for all future time, this discussion will be limited to missions from the sun out to Mars and possibly to Jupiter, but primarily to Venus and Mars. The following are likely space vehicle missions:

1) Probes (one way) to Venus and Mars, to impact or near miss

2) Probes (one way) to orbit Venus and Mars

3) Probes (one way) to land on Martian moons

4) Probes (round trip) to orbit Venus and Mars and return

5) Manned reconnaisance missions to pass by or orbit Venus and Mars and return

6) Manned missions to land on Martian moons, Mars, and possibly Venus, and return

7) Probes to Jupiter, Saturn, Mercury, and sun

These missions may take off from earth's surface, an earth satellite, or a lunar base. There may be more than one space vehicle simultaneously involved, particularly in (5) and (6). Table 2-2 shows the possible departure-destination relations, and some parameter values of interest. Trip times are for minimum or near-minimum energy. Small increases in velocity may result in large decreases in trip time. Doubling the Mars trip speed reduces the trip time to about one-seventh, for example. Though such a measure would be extremely expensive, reliability, psychological, and other considerations might make it worthwhile.

One of these other considerations is the supplies of food, air and water necessary for manned flights. One estimate available for lunar base support indicates 13.3 lbs per man per day, another gives 17.5 lbs per day. Assuming that advancements in technique will be made before a manned deep space mission occurs, 12 lbs per man per day is not unreasonable. This provides added compulsion to reduce trip times by increased speeds, but also competes strongly with communications gear for payload weight allocation.

In selecting a communication frequency, one important factor is attenuation or scattering by the earth's and possibly other planet's atmospheres. Impenetrability of cloud cover by a certain frequency need not necessarily exclude that frequency from consideration, however. At the earth end of the communication system, since cloud cover is never complete, numerous communication stations may be set up so that at least one will have a high probability of being in the clear. An earth satellite may be set up above the atmosphere to use as a relay station, using frequencies from satellite to earth which do penetrate clouds. A similar system can be arranged with a lunar base.

At the space end of the communication channel, Venus has complete and continual cloud cover; hence the multiple surface station solution is not feasible. In fact, preliminary exploration is necessary to determine frequencies which will penetrate the Venusian atmosphere, which is much different from Earth's and not now well known. Since Venus has no moons, the only remaining possibility for communicating from the Venusian surface by frequencies which are atmospherically absorbed is to go from the Venusian surface to a communication satellite by a penetrating frequency, and from there through space by the same or a nonpenetrating frequency.

Mars, on the other hand, has a visually but not necessarily electromagnetically transparent atmosphere, so far as is now known, except for occasional huge clouds interpreted as dust. Mars also has two moons, so that all three possibilities exist there--multiple surface stations, communication relay satellites, and moon relay bases. The Martian atmospheric transmission characteristics also require further investigation.

It is clear that each type of space mission must have a communications system designed as an integral part of the overall mission, since the environment and range of conditions is so radically different for each mission. It is quite possible that a choice of frequency for one mission would not serve for another. It seems very likely, for example, that at least for certain missions, a communication link between a space vehicle and an earth communications satellite at one frequency and between the satellite and earth at another frequency will prove to be the optimum.

4.2 SPACE SYSTEM REQUIREMENTS

Space vehicle missions requiring communication may be classified as to communications between planets and moons, planets and space vehicles, planets and planets, moons and space vehicles, space vehicles and space vehicles, and moon to moon. For each case there are pertinent variations in the existence of and importance of parameters that bound the communication system. These parameters include, for example, tracking rates, payload capabilities, energy sources, doppler shifts, signal transit times, background noise, general physical environment, local atmospheric effects, vehicle stabilization, fuel costs, solar radiation intensities, mission duration, and numerous others.

Payload Capability Estimates

The communications payload capability of various space vehicles is a function of booster and upper stage availability, vehicle destination, mission purpose, and weight allocation to communication in competition with other types of payload. The availability of boosters and missile stages changes with time, and it will be possible to draw more definite and useful profiles at a later date. At present, only the principal current systems and those under active development are listed (see Table 2-3).

TABLES 2-3. CURRENT SPACE VEHICLES

Booster	Second Stage	300-Mile Orbit Payload, pounds	Moon Landing Payload, pounds	Availability	Venus Payload Pounds
Thor	Agena B	5,300		Now	
Atlas	Agena B	5,000 to 5,800	600 to 1200	1965	600 to 1200
Atlas	Centaur	8,000	730 (hard landing) 100 to 300 (soft landing)	1965	1500
Titan II		6,280 to 9,375		1963-64	
Titan III		29,500		1965	
Saturn C1B		25,000		Being Launch-tested	

Most of the manned deep space vehicles will probably be launched by boost systems not on this list, such as the proposed Saturn V, Nova, Phoenix, or large solid boost systems. Figures 2-1 and 2-2 illustrate some of the payloads envisioned by mission type and booster category. The curves are actually broad uncertain bands.

A useful method of categorizing space vehicle missions is by velocity increments required. This relation comes about due to the nature of the well known fundamental rocket propulsion equations:

$$\text{Velocity} = gI_{SP} \log \left(\frac{W_{full}}{W_{empty}}\right) + gt \cos \Theta + \text{drag term}$$

The velocity attained is extremely sensitive to small variations of the ratio of full to empty weight. This sensitivity is further compounded when multistage rockets are considered. Therefore the slightest changes or faults in design can have major effects in mission-payload characteristics, and prediction in this field becomes increasingly hazardous as total required velocity and/or number of stages increases.

Some specific missions and their required velocities are given in Table 2-4. They are minimum energy, and thus long transfer time orbits. It may be desirable to sacrifice payload for a higher speed--and thus shorter time in space--for reliability reasons or for flexibility in the launch windows. While a one-way Venus probe may take about 4 months and to Mars 8 months, a trip to Venus and return will take over 2 years, and to Mars and return 2.66 years. This time is mostly spent waiting at the planet for an appropriate time (i.e , position relative to earth) to start the return trip.

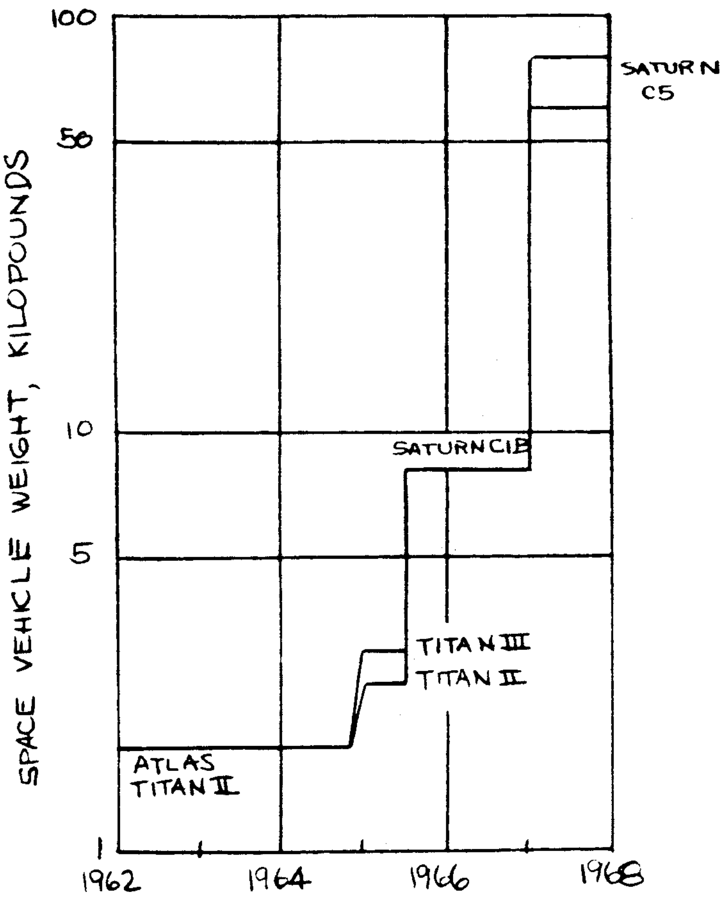


FIGURE 2-1 ESTIMATE OF SPACE VEHICLE WEIGHTS FOR VENUS OR MARS TRIP

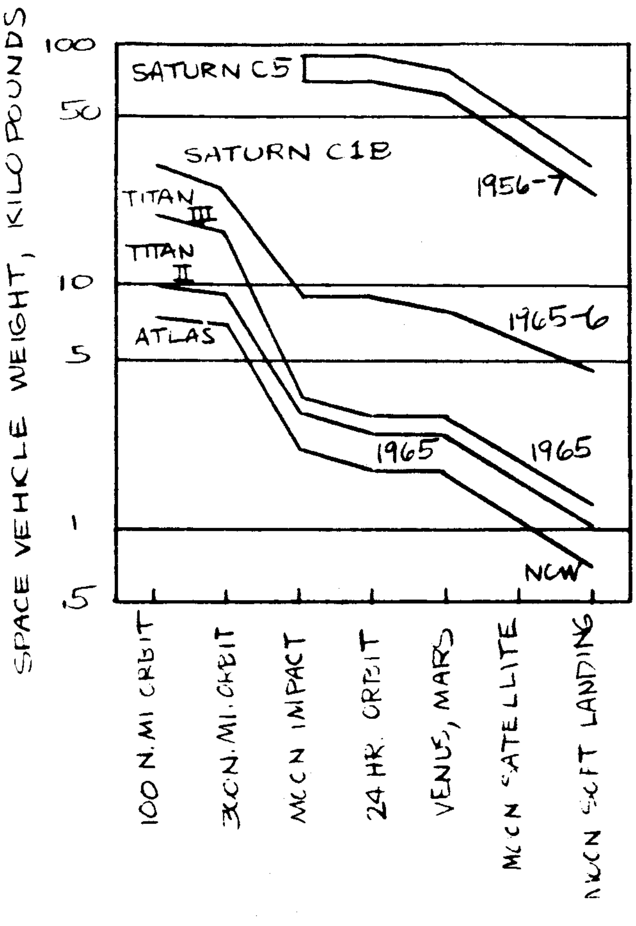


FIGURE 2-2 ESTIMATE OF SPACE VEHICLE WEIGHT CAPABILITY

TABLE 2-4. REQUIRED MISSION VELOCITIES

Mission	Velocity, fps
Earth satellite (300 nautical miles)	24,000 +
Earth escape	36,680
Flight to sun	46,583
Flight to Venus	38,220
Flight to Mars	38,579
Orbit of moon	38,000
Soft lunar landing	44,300
Orbit Venus at 2000 nautical miles	47,410
Orbit Mars at 6000 mautical miles	44.700
Land on Mars and return	56,700 to 100,000

In the case of one-way probes, it may be possible by increasing speed, at some sacrifice in payload, to reduce the distance from earth to Mars (or Venus) at the time of impact. This may have compensating advantages in reduced range for telemetry transmission and therefore reduced power and eased tracking requirements. The problem of interplanetary orbital mechanics is exceedingly complex, and while it should not be explored in detail in this study, those points pertinent to communications must be examined with care.

The manner in which the velocity increments may be separated is illustrated in Table 2-5.

TABLE 2-5. SOFT LUNAR LANDING AND RETURN

Mission	Velocity, fps
Earth satellite velocity	25,000
Leave earth satellite orbit	10,000
Enter moon orbit	2.000
Land on moon	5.700
Launch from moon	5,700
Leave moon orbit	2,200
Enter earth satellite orbit	10,000

These tables are included, not to enable design of a space vehicle, but to illustrate the highly "tailored" quality of such design and to imply the high dependence of payload on the particular mission character.

The mission purpose (as distinct from its path) will also strongly affect the communications payload. Very highly instrumented experimental vehicles will require large amounts of telemetry; proven designs with only logistic functions will need less. Man-carrying vehicles will need more communications; vehicles carrying continuously operating or real time equipment, experiments, or data sources will need more.

Problems of priority will arise when the always-limited payload must be allocated among the many items to be carried besides communications. These problems are closely allied to the mission purpose but also involve large elements of pure judgment and are for the most part not easily quantifiable.

How to decide, for example, the relative worth of a safety device for manned vehicle as compared to an increment of communication capability?

Energy Sources

Communication requires energy. The energy must be obtained from some source, converted into usable form--usually electrical energy, and the waste energy radiated into space. There is an extensive and rapidly growing experience and literature in this field, and only a synopsis is given here.

The practical schemes for energy sources comprise three types: those using solar energy and thus carrying no fuel; those carrying fuel, which has weight and is expended; and nuclear sources, whose "fuel" is essentially weightless.

Solar energy sources will require smaller collecting arrays on Venus trips than on Mars trips, due to the proximity of the sun. The solar constant goes from 1.94 cal/cm^2/minute at the earth to about 3.71 cal/cm^2/minute at Venus, but to about 0.84 cal/cm^2/minute at Mars.

For space vehicles which need energy only or mostly at or near Venus, the solar collectors can be about half the size of those near earth. For vehicles needing power all the way, either auxiliary sources for the near-earth portion of flight or larger collectors must be used, which will result in a considerable reserve at Venus.

On the other hand, Martian trips will require solar collectors about 2.5 times the size of those needed near earth. Actually the solar radiation made available must be tailored to the energy demand profile, based on mission requirements.

The solar radiation can be used for direct conversion to low-voltage direct current by devices such as solar silicon cells. These devices suffer from meteoritic erosion, radiation, and other space environmental effects. Estimates of time to decay to 75 percent of original performance run from 3 months to 10 years. Furthermore, they decrease in efficiency at higher temperatures, the efficiencies near Venus, Earth and Mars being about 7.8 percent, 9.3 percent and 10.8 percent so that solar cell arrays must have areas per kilowatt of 50 ft^2, 85 ft^2, and 165 ft^2 respectively. The sunlight collected may be used for turboalternator, thermocouple, and thermionic generating devices as well, each having its own characteristics and potential utility.

Chemical, or fuel carrying power sources, have lives limited by the quantity and storability of fuel as well as the other factors affecting reliability. Types of sources are batteries, fuel cells, magneto-hydrodynamic generators, turbogenerators, and reciprocating engines. These are not expected to be practical as primary communications power sources due to the heavy fuels.

Nuclear radiation sources comprise those using radioisotopes and reactors. The radioisotope sources have an exponential decay of power; the reactors maintain constant power availability until the fuel is used or reliability problems intervene. Nuclear sources require shielding in some proportion to their power output

Some of the energy sources produce usable electric power directly. Most must use some form of converters to provide the power in usable electric form. No such system has perfect efficiency, and power systems must discard waste power. This can only be done, on long space missions, by radiation.

The size and efficiency of the radiators are a strong function of the temperature of the radiating surface. It is possible to use combinations of power sources and converters which work in various temperature regions so that one utilizes the exhaust power from another, and thus to improve the overall efficiency, but in no instance can a heat engine use all the power input. Radiators are subject, as are solar panels, to erosion and meteoric puncture; hence redundant radiators, shielding, etc., are used at rather heavy cost. For some characteristic radiators, doubling the wall thickness (and thus the weight) gives an order of magnitude decrease in penetrations per unit area per unit time. A radiator weighing 9 lb/ft^2 would be expected to suffer 2×10^{-3} penetrations per square foot per year, for example. For a perfectly black radiator facing space only, the minimum area needed per kilowatt of emitted power is

$$\left(\frac{S}{P}\right) = \frac{1}{\sigma T^4}$$

where $\sigma = 5.1 \times 10^{-12}$ $KW/ft^2/(\text{deg Kelvin})^4$

and T = radiator temperature in degrees Kelvin.

Table 2-6 gives some pertinent data on current and near-future power source development. This list is far from complete. It appears, however, that for space vehicles requiring operation for periods of months to years that solar cells, solar collectors and nuclear fission devices are the most promising.

TABLE 2-6 POWER SOURCES

System	Conversion	Power Range kw	Weight Unshielded, pounds	Watts per Pound	Design Life, years	Operational Date	Fuel Consumption, lb/kw-hr
SOLAR							
Solar cells	Photo voltaic	0 to 1	0 to 1000	1 to 25	Several	Current	
Solar collector	Thermionic	0.1 to 0.25	20 to 50	5	1		
Solar collector	Turboelectric	1.5 to 15	300 to 3000	5	1 to 2		
Solar collector	Turboelectric	34	2300 to 2800	1.2 to 1.5	1.14		
Solar collector	Turboelectric	3	700	4.3	1		
Solar collector	Turboelectric	30	1800	1.67	1		
Solar collector	Turboelectric (Sterling engine)	4	500	8			
CHEMICAL							
H_2O_2 fuel cell		0.9	83	10.8	0.114		3 to 6
LI H_2 fuel cell		0.5	127	3.9	1		
Magnetohydrodynamic		50	143	350	0.0001		
Turbo alternator-closed cycle H_2O_2		100	240	416	0.05		1.6
Turbo alternator-open cycle H_2O_2		100	50	2000	0.05		1.7
Turbo alternator-open cycle H_2O_2		1	25	40	0.05		2 [illegible]
Lead acid battery					0.05	Current	50
Cadmium silver battery					0.5	Current	33

TABLE 9-6 (Continued)

System	Conversion	Power Range kw	Weight Unshielded pounds	Watts per Pound	Design Life, Years	Opera-tional Date	Fuel Con-sumption, lb/kw-hr
RADIOISOTOPE							
SNAP 3 - P - 210	Thermoelectric	0.003	4	0.8	0.25	Current	
Transit IV-P_u-238	Thermoelectric	0.0027	4.6	0.6	5	Current	
SNAP 9A-P_u-238	Thermoelectric	0.025	27	1			
SNAP 11-C_m-242	Thermoelectric	0.025	30	1	0.25	1964	
SNAP 13-C_m-242	Thermionic	0.025	8	3			
Comsat-S-90	Thermoelectric	0.15 to 0.25	150 to 250	1	> 5	1965	
Radioisotope-C_e-144	Thermionic	0.5	< 300	>1.7	1	1965	
Radioisotope-C_m-244	Thermionic	0.5	< 200	>2.5	> 1	1965	
REACTOR							
SNAP 10 A	Thermoelectric	0.5	525	0.95	1	1964	
SNAP 2	Turboelectric	2	865	2.3	1	1965	
SNAP 8	Turboelectric	30	1700	17.6	1.14	1966	
SNAP 8(1)	Turboelectric	60	2700	22	1.14		
STAR-R	Thermionic	70	1400	50	1		
START	Thermionic	60	1000	60	1		
SPUR	Turboelectric	300	2800	107	1.14		
T/1 reactor	Thermionic	300	1200	250	1		
DCR-300	Thermionic	300	1900	158	1		
SNAP 50	Turboelectric	100 to 1000				1970	

Acquisition and Tracking

In deep space communications, of the order of a hundred million miles range, communication system power will be at a premium; therefore, the maximum feasible antenna gain must be used. This means narrow beams, introducing an acquisition and a tracking problem.

Space vehicles must move in very accurately known trajectories. A probe sent to Venus, for example, will miss the planet entirely if the speed is in error by 0.5 fps in a total of about 38,000 fps. Continued tracking of the spacecraft can be maintained and minor corrections made to ensure the proper trajectory. The point here is that spacecraft postions will always be known to very close tolerances; thus acquisition of communicating stations by the spacecraft should present no particular state of the art problems. Acquisition under such circumstances becomes mostly a computation and pointing problem, though such computations must take account of the velocity of light and lead the target accordingly, since one-way transmission may take as much as a quarter hour of transit time.

Engineering practice for the controlled pointing of an infrared gimballing system is currently 15 microradians. Present good resolvers have readout accuracies of 100 microradians, with 5 microradians promised by some. Pointing stabilities of the order of 0.1 to 1.0 microradian are achieved at present by astronomical devices on the earth. It would seem then that acquisition could be performed without scanning, by a single look, with beam widths of the order of 15 microradians or larger provided adequate platform stabilization can be achieved. A diffraction limited antenna of 1 meter diameter cannot produce a beam this narrow at wavelengths longer than 0.012 mm, to set the perspective. The larger the beam angle, the easier the acquisition and the less the dependence on good platform stabilization and accurate position and attitude computation. However, requirements go up as the square of beam angle.

Tracking can be carried out with the communication beam or with auxiliary equipment. Astronomical telescope star tracking systems, although an optical method, are presently being made with tracking accuracy of the order of 0.5 microradian. Star tracking systems--passive trackers--for use on earth satellites and space vehicles now are claimed accurate to 5 microradians. Space probes could track any known star, moon, or planet and then position the communication beam accordingly. For cummunication with moons or planets having no atmosphere, either passive or active tracking is possible on light sources at the station tracked, subject to weather interference on planets having an atmosphere. This method would avoid the dark phase problem, which, however, might not be severe, since complete dark phase conditions would be rare and transitory and there are numerous alternate tracking points available in space.

A plausible scheme might be to optically acquire and track a powerful ruby laser flashed at frequent intervals and to align the communication beam to the desired communication station by proper computations involving the trajectories and signal transit times. The required beam width would then be determined by platform and tracking stabilization and computational accuracy and could be as narrow as of the order of 15 microradians. This would give the minimum power requirement, and other practical factors would then be considered which would be traded off against increased beam width and therefore increased power.

If the communication station being tracked were located on a planetary satellite, the orbital period of the satellite could easily be of the order of signal transit times. This situation could lead to tracking problems. At long ranges, a solution could be to track the earth, using beamwidths sufficiently wide to include the entire satellite orbit.

Close to earth, however, this solution requires enormous beam widths. Therefore the preferable solution will probably be to track the satellite itself and accept the added computational complexity of eclipse problems, etc. Use of a 24-hour synchronous satellite or synodic satellites might be a preferable solution, or a moon station, with relay capabilities.

Tracking space vehicles from other space vehicles may be more difficult. Here the distances will usually be much smaller, but relative positions not quite so accurately known. It would seem that use of high power lasers for optical acquisition, followed by tracking by optical, radar, or communications beam means, would be quite feasible.

Spacecraft Stabilization

As pointed out in the discussion of acquisition and tracking, it is important that the spacecraft be adequately stabilized so that narrow communication beams may be used and low power and low weight systems evolved. In both manned and unmanned space vehicles, vibrations and mechanical perturbations will be induced internally by rotating and vibrating machinery, thermal flexing of the spacecraft, operation of the stabilizing controls themselves, motion of tracking antennas, solar panels, cameras, and orientable instruments of various sorts, and shifts of center of gravity as fuels slosh and are expended and wastes disposed of overboard. In manned craft, the slightest motion of personnel--even their breathing while asleep--will cause spacecraft motions which could conceivably interfere with communication tracking and acquisition and therefore must be considered in the design.

There are also external perturbing forces such as meteoritic impact and the effects of gravitation of planets and moons in the vicinity. For many reasons, it is not always adequate to permit a space vehicle merely to drift in space, even if it were sufficiently stable otherwise. It often will be necessary to continually or periodically reorient the vehicle attitude as the trajectory changes with time. Many earth satellites currently are adequately stabilized to the order of about 1 degree in attitude. The pending Orbiting Astronomical Earth satellites will require temporary stabilization to astronomical standards (about 0.5 microradian) in order to obtain adequate resolution of astronomical photographs, and this is apparently within the current state of the art. For true deep space missions, it will almost certainly be necessary to mount the communication antenna on a stable platform. If the vehicle is manned, personnel movements will be so uncertain and of such magnitude as perhaps to require a very much decoupled system, possibly even a separate vehicle or a detached "pod", self-stabilized and recoverable. The need for such drastic measures will depend on the results of the tradeoffs which can be made between communication beam stabilization, beam angle, power, and weight under the particular mission vibration, perturbation, range, and other requirements. In missions requiring extreme precision of control (long ranges and narrow beams) the entire vehicle may be stabilized, but if economy in control capacity is paramount, a small platform should be stabilized.

2.3 COMMUNICATION CHANNEL CHARACTERISTICS

When selecting a communication or telemetry system, consideration must be given to the characteristics of the channel in order that the signal may be properly tailored for its optimum use. The principal element in channel characterization is the presence of background noise and attenuation. If no noise were present, there would be no limit on the range of a transmitted signal since the received energy could be amplified as much as necessary to regain the intelligence. Noise affects the range in several ways. At the transmitter, it affects the stability and clarity of the signal. It influences the intensity, direction, and spectral characteristics of the transmitter-receiver space link. At the receiver, the noise is temperature and bandwidth-dependent. It also affects the receiver oscillator stability and purity. The three basic sources for noise in the entire frequency spectrum are: background, transmitter and receiver. They are treated independently in this report.

Background Noise and Attenuation

For deep space telemetry, two completely different noise environments can exist. They depend on the source-destination relationship and, in particular, on whether the communication path is between space and earth or between two space locations.

The essential difference between these cases is the presence of the earth's atmosphere and interfering radiation which results from man-made noise. The latter can be reduced considerably by the selection of a remote operating site. The former, however, must be considered strongly in the establishment of the optimum operating frequency.

The earth's atmosphere has essentially two effects on communications. First, it attenuates the incoming signal within the system passband, and second, it serves as a filter-converter of the signal and incoming extra-atmospheric background radiation. Thus radiations which might normally lie outside the passband of the receiver in a communication system operating from a space transmitter to a space receiver is converted into noise radiation in the signal portion of the spectrum for a communication system which involves the atmosphere as part of the communication channel. Conversely, noise in the passband which would be a source of interference in deep space is filtered out by the atmosphere if the receiver is located on the earth. The principal degradation, however, results from the signal being not only attenuated but also converted to noise within the passband of the receiver by means of forward scattering and absorption/reradiation processes. Thus, conditions for operation through the atmosphere can differ quite significantly from those in deep space. Some of these significant differences are discussed here and estimates are given of the magnitudes of the individual noise contributions.

Radio Noise

The background noise has a variety of sources and frequency distribution bands. One of the greatest sources of noise is the earth itself. The earth's atmosphere, besides absorbing selected frequencies, generates some of its own, principally by lightning discharges in thunderstorms. All the atmospheric radio noise is dependent on frequency, weather, time of day, year, and geographical position. For radio communication at frequencies below 50 mc, atmospheric noise is usually the limiting factor. A plot of noise versus frequency is given in Figure 2-3 for both night-time and daytime. The graph shows a sharp rise in noise with decreasing frequency. Other types of noise are shown to scale on the same plot for comparison.

Radio noise can be classified in three distinct sources: 1) man-made, from motors, appliances, etc.; 2) inherent, from thermal agitation, shot effect, etc., in the equipment; and 3) natural, from space, atmosphere, etc. To interfere, the noise must enter the receiver passband. The noise may contain frequencies in the sensitivity band, or sufficiently close and with sufficient strength to enter the "extended" bandwidth. It may combine (hetrodyne) with another frequency in some nonlinear element and generate a new frequency in the passband.

Man-made noise is a considerable problem when the earth is one of the communication stations. This man-made noise takes the form of electrical, wide-band disturbances from such sources as autoignition, motors, generators, and high-tension lines. Figure 2-3 shows this noise as a function of frequency for both urban and suburban areas.

The sun puts out noise in bursts principally in the 100 to 580 mc band. Noise storms occur on the sun that have a long series of short bursts continuing for hours or days. These short bursts of noise are superimposed on a background of slow varying radiation. Most of these storms have a wide frequency distribution but rarely exceed 250 mc. Some have bandwidths of a few megacycles and last from a fraction of a second to almost a minute. Others may have a bandwidth of nearly 30 mc and rarely exceed 1-second lifetime. A slow noise burst is usually narrow band and intense. It usually drifts down in frequency gradually and sometimes irregularly. The fast bursts are very common and have a fast drift down in frequency.

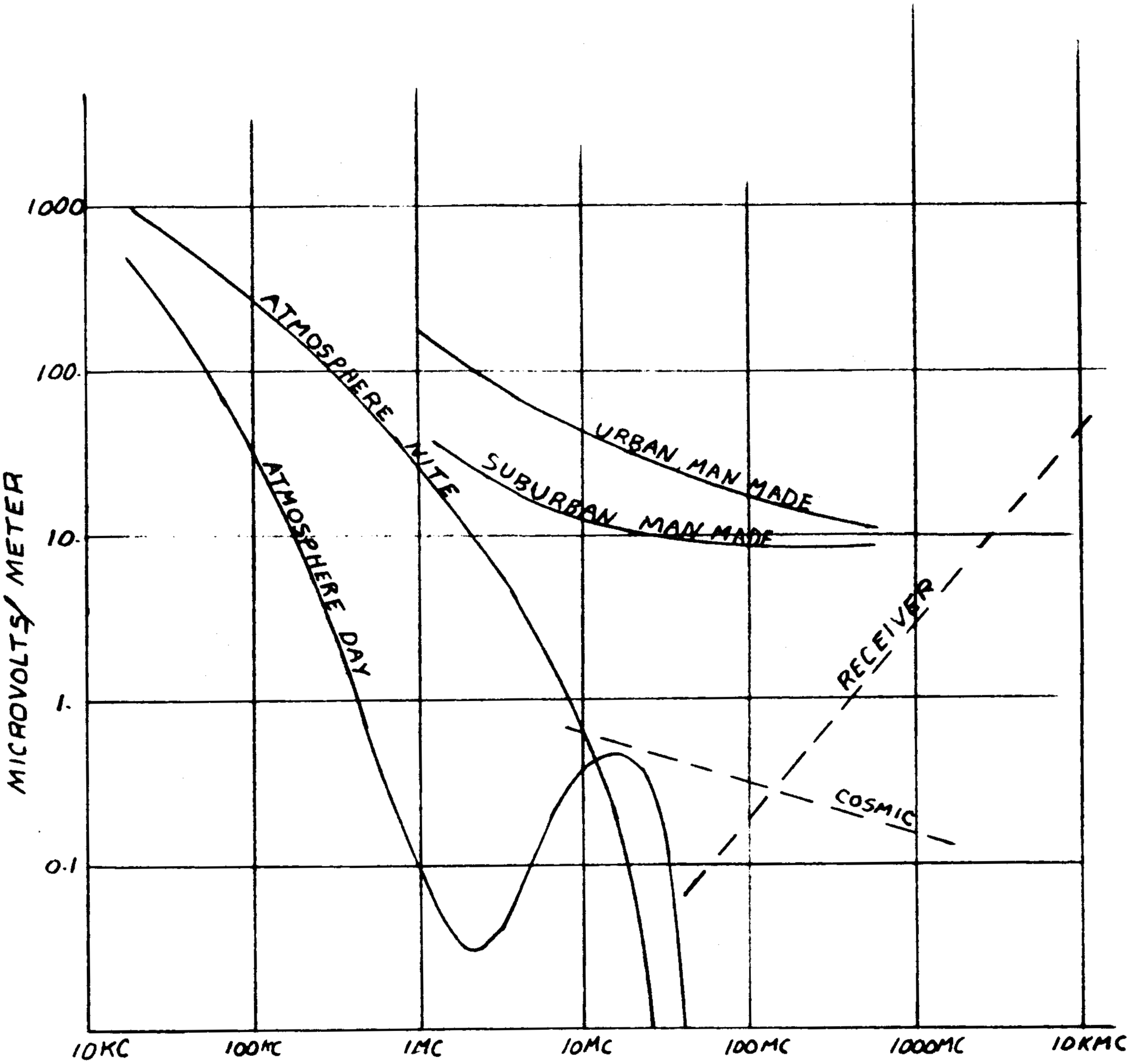
In general, external noise is a function of frequency. The lower the frequency, the greater the interference. This effect is illustrated in several curves in Figure 2-3.

Cosmic Noise

The most difficult to investigate from a point on earth is solar and cosmic noise, shown in Figure 2-8. The sun is the greatest noise source to consider from anywhere in the solar system. Its corona is not terminated in a finely divided line but extends with diminishing effect several million miles out into space. Dust particles scatter and diffuse the light and RF energy, making its effect noticeable in all directions. At earth radius (1 astronomical unit) from the sun, there is still about 2 cal/cm^2/min of energy available; 99.8 percent of this energy is in the 0.2 to 0.7 micron band.

The nine planets and their 31 moons and the asteroidal belt, comets and dust generate some noise, although it is slight compared to the sun. Venus, the planet with the greatest reflectivity, emits about 1 erg/cm^2/sec at 10^7 km distance. Most solar system bodies without atmospheres have thermal radiation close to that of a standard blackbody radiator at the surface temperature. Thermal radiation from atmospheric bodies is dependent on the wavelength and surface position. Venus, for example, is equivalent

FIGURE 2-3
RADIO NOISE*



10 KC BANDWIDTH
HALF WAVE DIPOLE ANT.

* REFERENCE DATA FOR RADIO ENGINEERS (IT&T)

to 250° K at 10 microns and 600° K at the centimeter frequencies.

Other sources of noise exist outside the solar system. The greatest in the near-visible band occurs toward the center of the Milky Way. The type of energy emitted is very similar to that from the sun.

The entire sky has about 10^{-3} ergs/cm^2/sec, compared to the visible air glow of 16×10^{-3} ergs/cm^2/sec. The radiation density has been estimated at 12×10^{-13} ergs/cm^2/sec, which is equivalent to about 3°K. The sky is not uniformly bright; estimates place it at about 700 (visual magnitude of 10) stars per square-degree toward the galactic center and about 35 stars per square degree toward the galactic poles

At radio frequencies, the sky contains over 600 discrete radio noises. Ninety-eight percent of each have energies more than 6×10^{-23} ergs/cm^2/cps and a temperature greater than 10^{4}°K at 1.7 meters. Their cone angle is somewhat less than 1/2 degree (the apparent diameter of the sun and moon). The overall sky brightness mean temperature is about 700°K at 3 meters. At the galactic center, it is 2×10^{4}°K at 30 meters to less than 10°K at 10 cm. The brightest source, Orion, has 2×10^{-5} ergs/cm^2/sec, where the total flux in this region from all sources is about five times as great. Figure 2-4 shows a comparative plot of several noise sources.

For frequencies above 50 mc, atmospheric noise is of diminishing importance and becomes negligible with respect to other factors at gigacycle (1000 mc) frequencies. At these higher frequencies, the effective antenna noise temperature results from many other sources, principally the atmospheric absorption noise and earth radiation noise, as well as the previously discussed galactic, stellar, and planetary noise.

Earth radiation noise is important especially for a space receiver that must look at the earth background with its main or sidelobes and for a ground-based antenna that has increased antenna noise from its back or sidelobes. This contribution can be typically as much as 20°K. Recent antenna designs that place the focus of the parabola below the rim for near zenith viewing help keep this figure low.

Atmospheric Attenuation

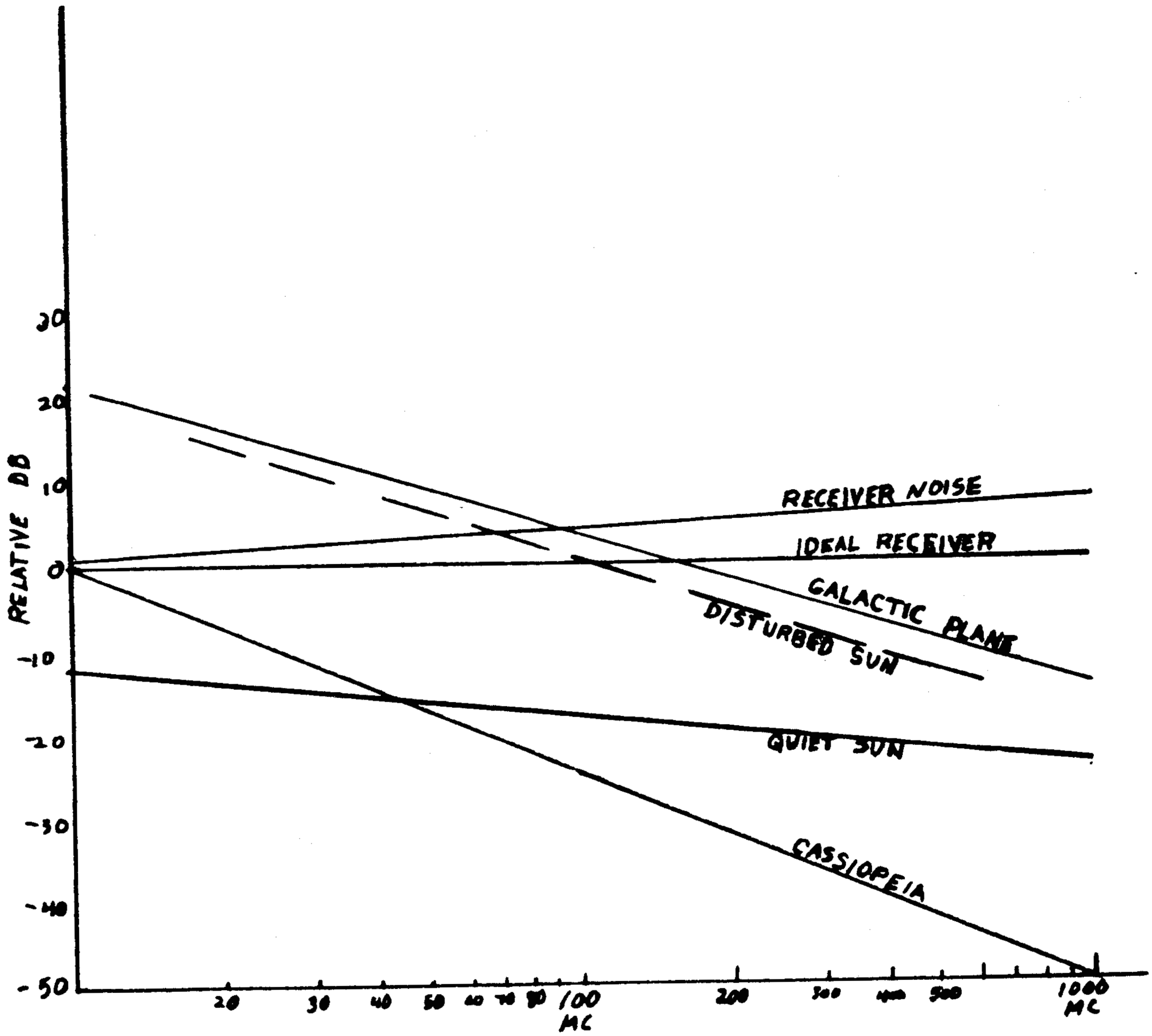
For earth-space or space-space communication the line of sight condition predominates. Even communication to the back side of the earth or moon will be line of sight, with the aid of one or more relay stations. Propagation computations are simplified under these conditions.

When transmitting through the earth's atmosphere determination of the propagation characteristics becomes complex due to the atmospheric attenuation. The absorption characteristics are well known for certain frequency bands. Figure 2-5 shows a portion of the spectrum for the earth's atmosphere only.

Figures 2-6A, 2-6B and 2-7 shows the approximate attenuation characteristics of our atmosphere. It is transparent in some regions such as most of the 1μ to 14μ band. There are several opaque regions here also due to absorption of energy by water vapor, carbon dioxide, carbon monoxide, ozone, methane and nitrous oxide. The 14 to 1 mm band is entirely opaque due to

FIGURE 2-4*

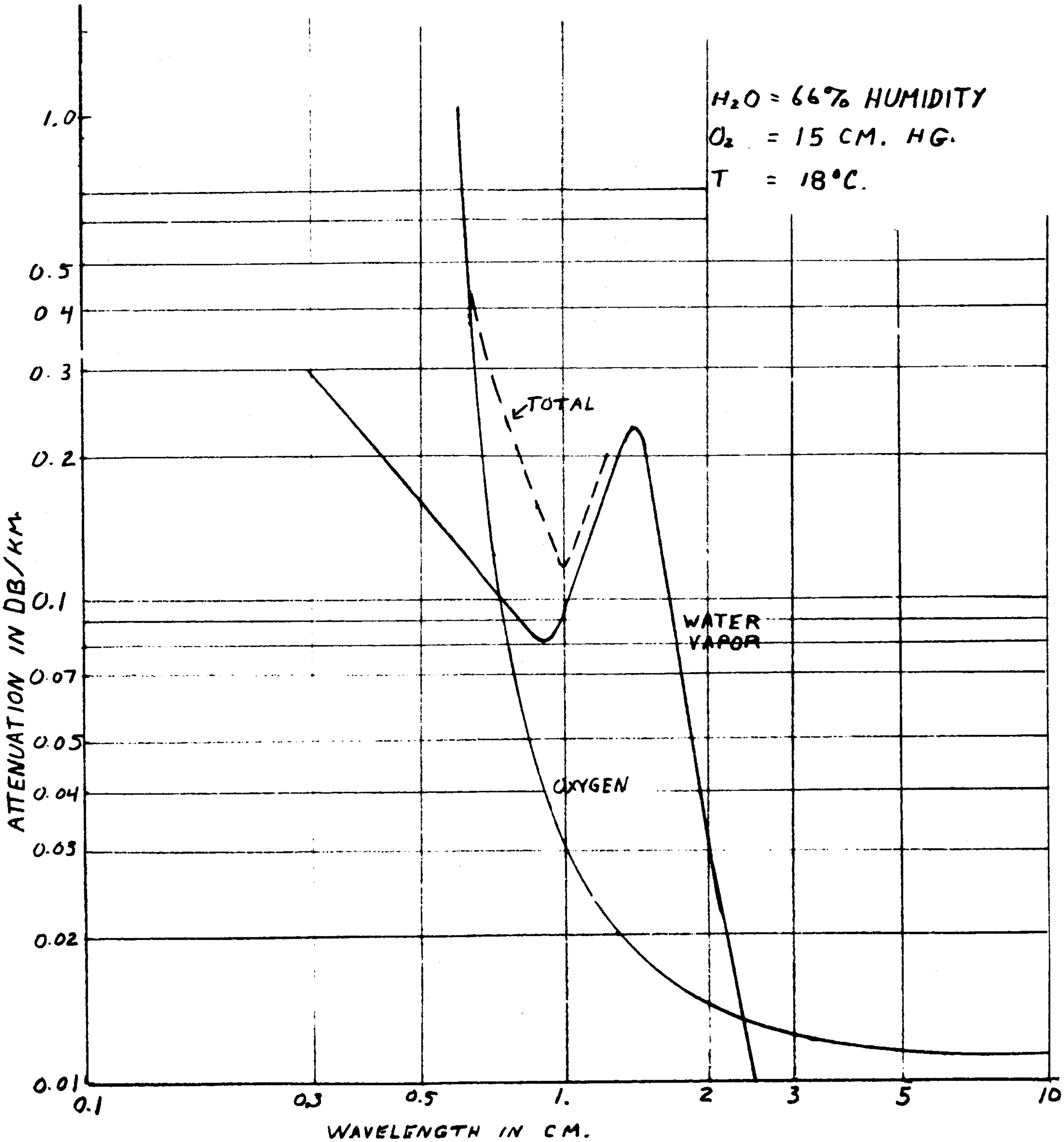
COSMIC AND SOLAR R.F. NOISE



* REF. DATA FOR RADIO ENGINEERS. (IT&T)

FIGURE 2-5

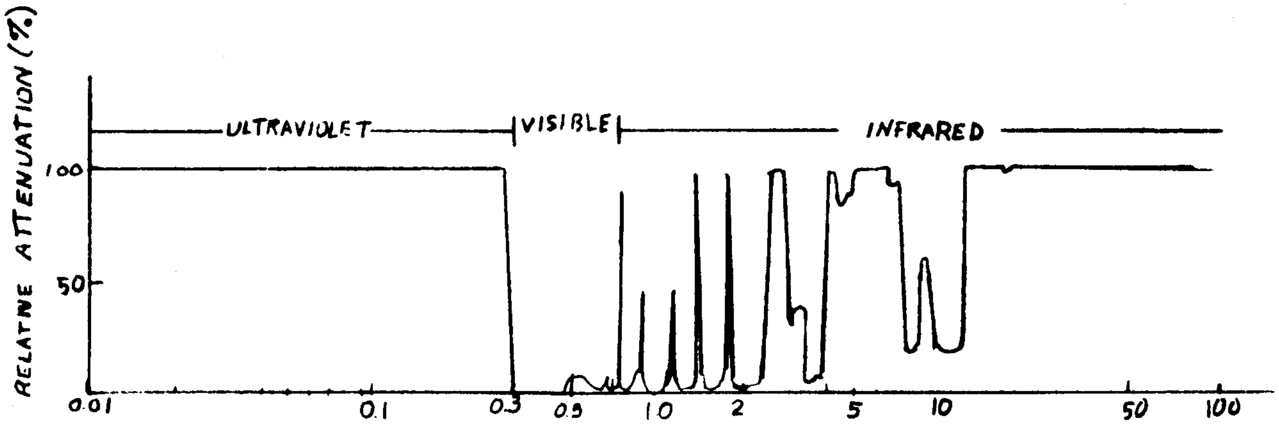
ATMOSPHERIC ABSORPTION*



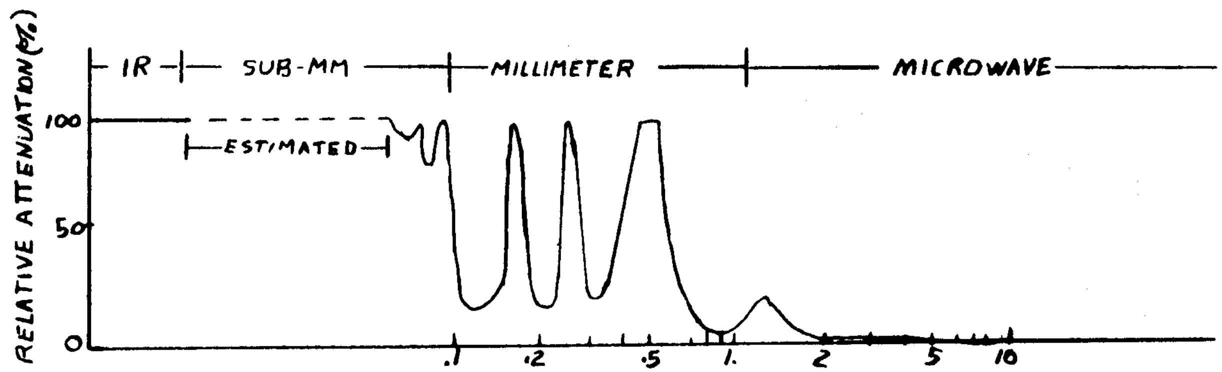
* (IT&T) REF. DATA FOR RADIO ENGRS.

FIGURE 2-6
ATMOSPHERE ATTENUATION

(A)



(B)



SLANT ATMOSPHERIC ATTENUATION
MULTIPLICATION FACTOR

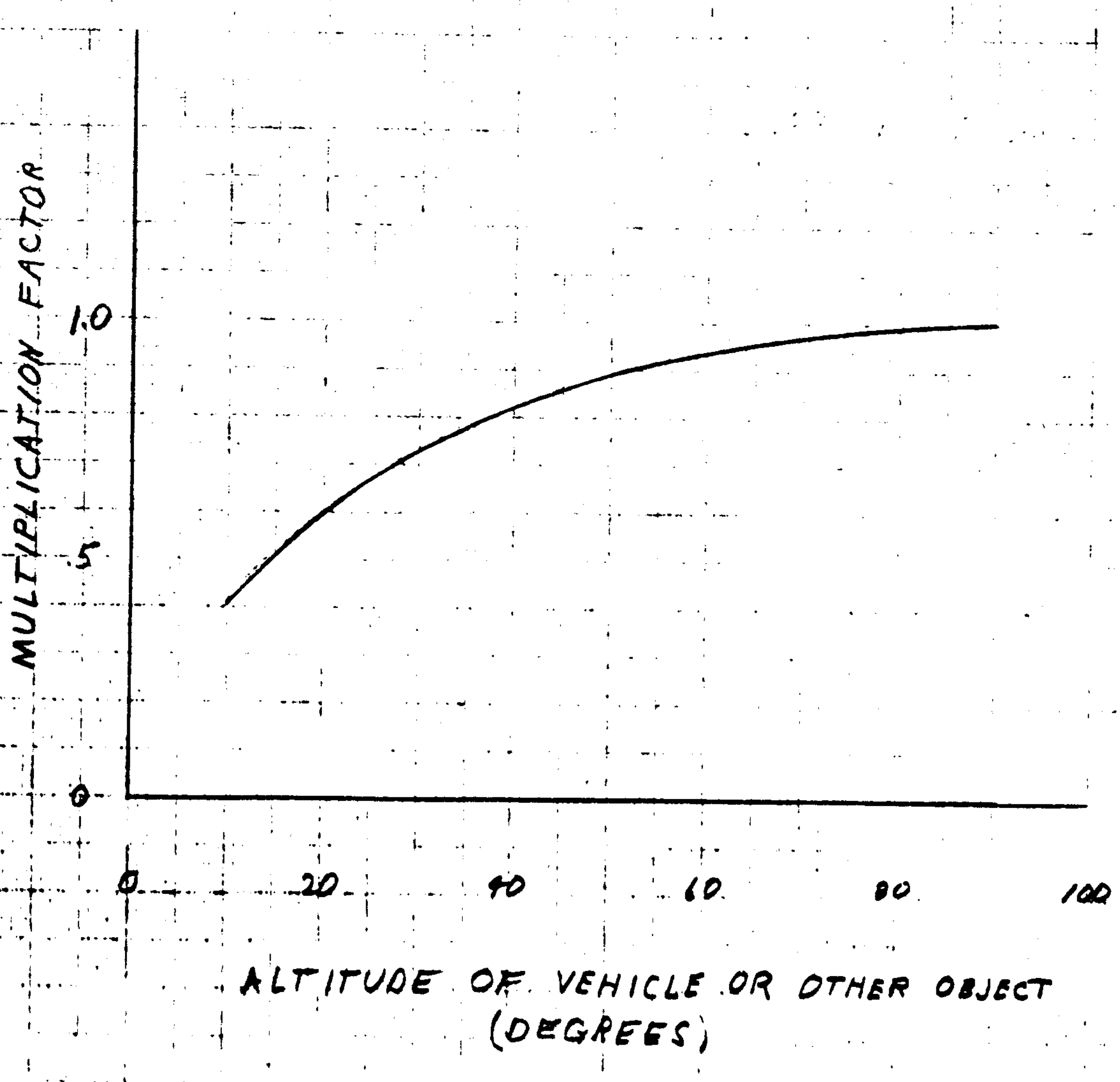


FIGURE 2-7

water vapor absorption. From 1 mm to 20 meters the atmosphere is transparent. Above 20 meters all the energy is absorbed or reflected by the ionosphere. Clouds, if present, are severe attenuators of some portions of the spectrum such as 1.25 cm. Figure 2-5 shows the water vapor absorption characteristics. The thickness of the atmosphere affects the attenuation. When looking through the atmosphere at some slant angle the attenuation is greater. Figure 2-7 gives a multiplication factor as a function of the altitude angle.

When considering other planets atmospheres of different composition and densities, new attenuation characteristics must be derived. This includes the sun's corona when the communication link is between two points near opposition.

Sky Irradiance

In the near visual portion of the spectrum the sky exhibits tremendous changes in irradiance depending on the conditions. During the day the diffused sunlight causes it to glow very bright. Cloud cover influences it considerably making it brighter or dimmer depending on the location of the observer. The moon phases causes changes in the night sky that are very noticeable. Starlight, eclipses, snow reflections, etc. greatly alter the radiance. Figures 2-8 and 2-9 show the radiated power under some of these conditions. Many factors influence this such as elevation angle of viewer, latitude, season, altitude, time of day, and many more.

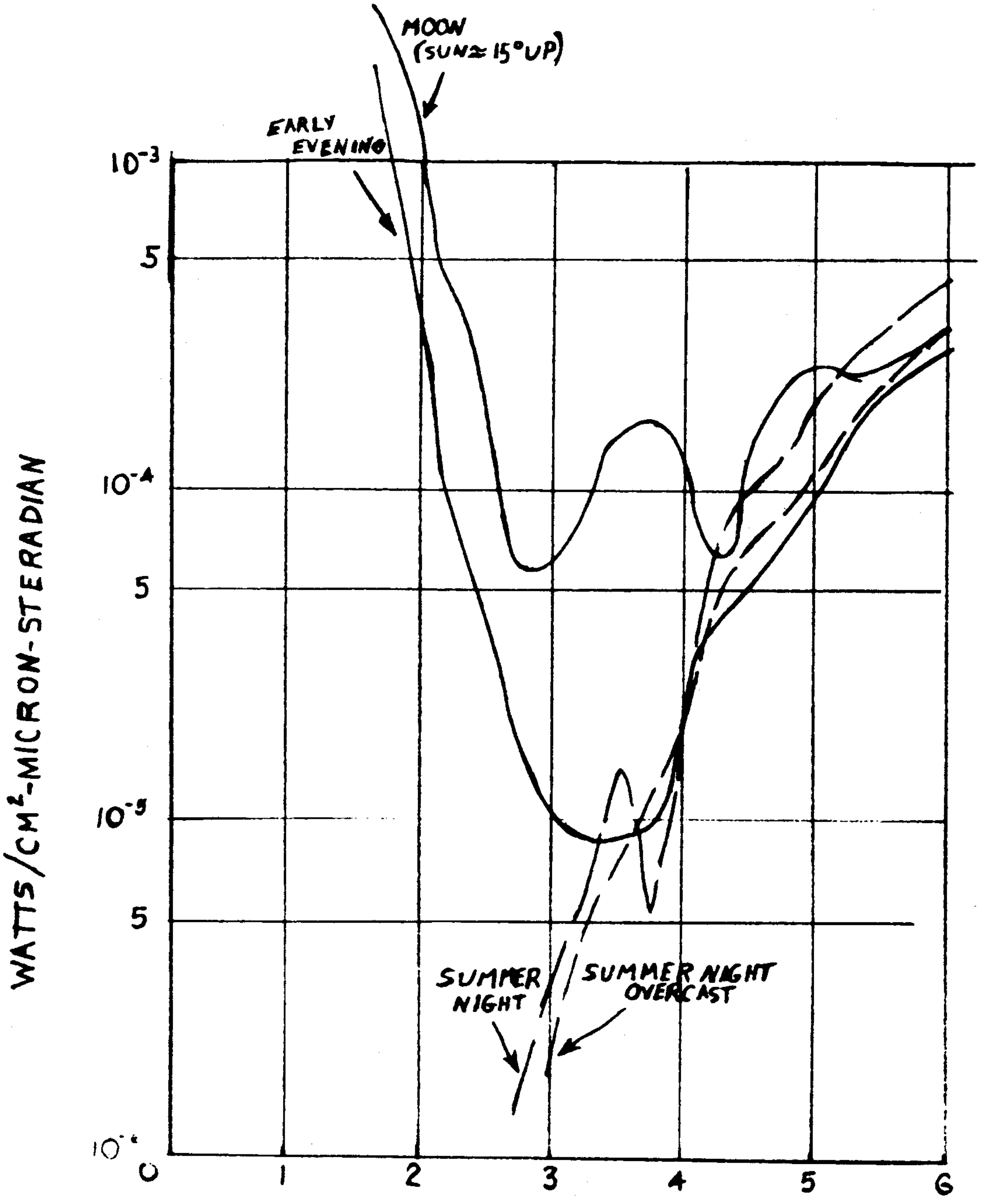
Sky Noise Temperature

In the radio frequency spectrum the sky also has radiation. This is usually measured in an equivalent black body temperature. Some of the major contributors to this form of noise are oxygen and water. Figure 2-10 shows the amount of temperature contributed by these as plotted against frequency for several elevation look angles. It is most severe when looking near the horizon. There is a peak at about 22,000 megacycles due to the water alone.

When looking at the total noise temperature, (sufficiently removed from cities and other sources of man made noise) a curve is obtained as shown in Figure 2-11. The low point is the preferred region to operate in and it appears at about the 5 to 8 gigacycle band.

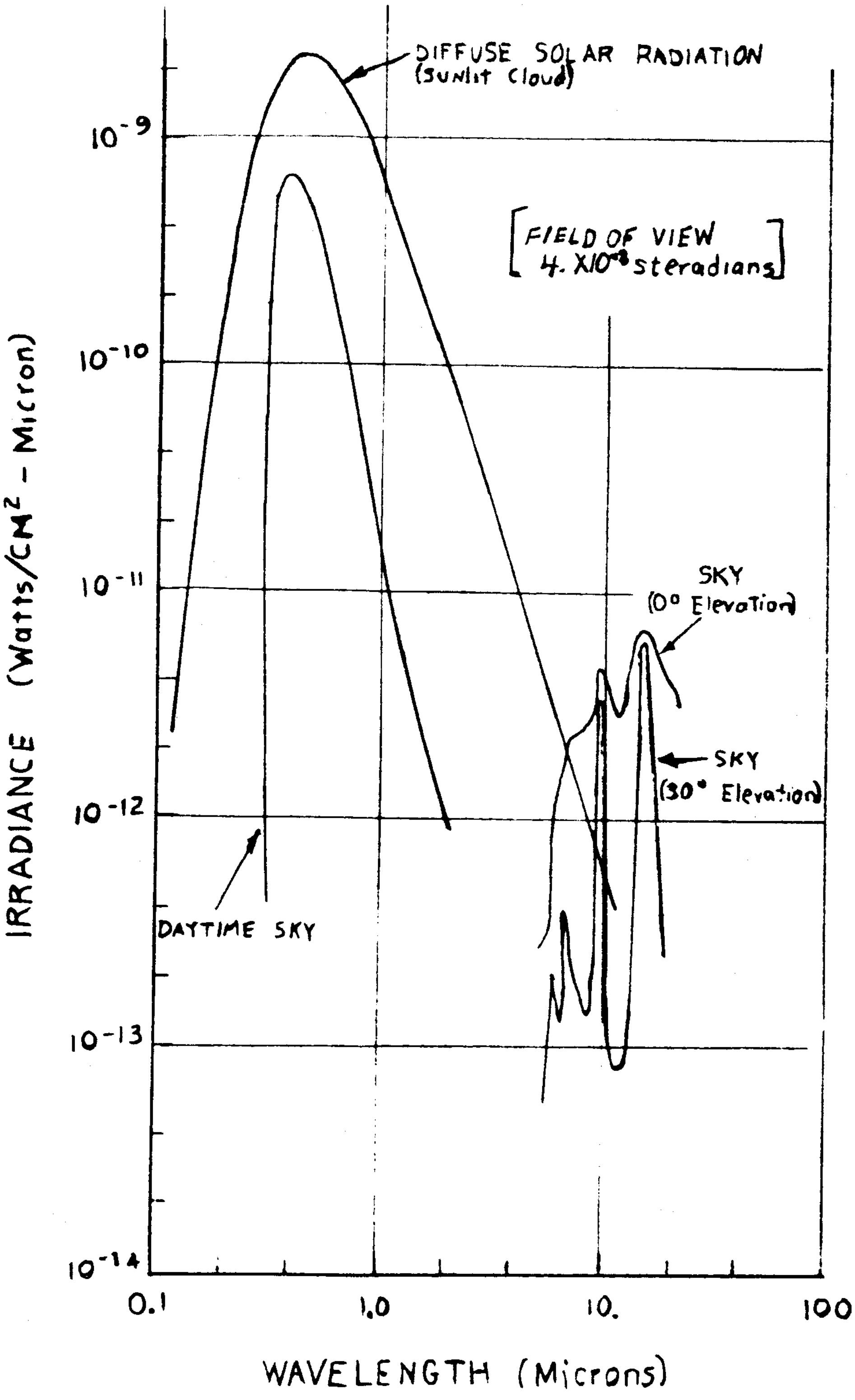
Atmospheric Distortions

An optical space to earth communication must penetrate the atmosphere. This ocean of gases affects the desired signal in many ways, almost all undesirable from the communications point of view. It masks the signal during the daylight hours by diffused sunlight and to a lesser extent at night by scattering the starlight and moonlight. It attenuates the signal severely in many spectral bands, becoming entirely opaque in some and remaining nearly transparent in still others. Even in the atmospheric windows the signal is distorted in many ways. These perturbations principally take the form of refraction, image motion, pulsations, and scintillation. The latter three relate to the turbulence of the atmosphere.



SKY IRRADIANCE

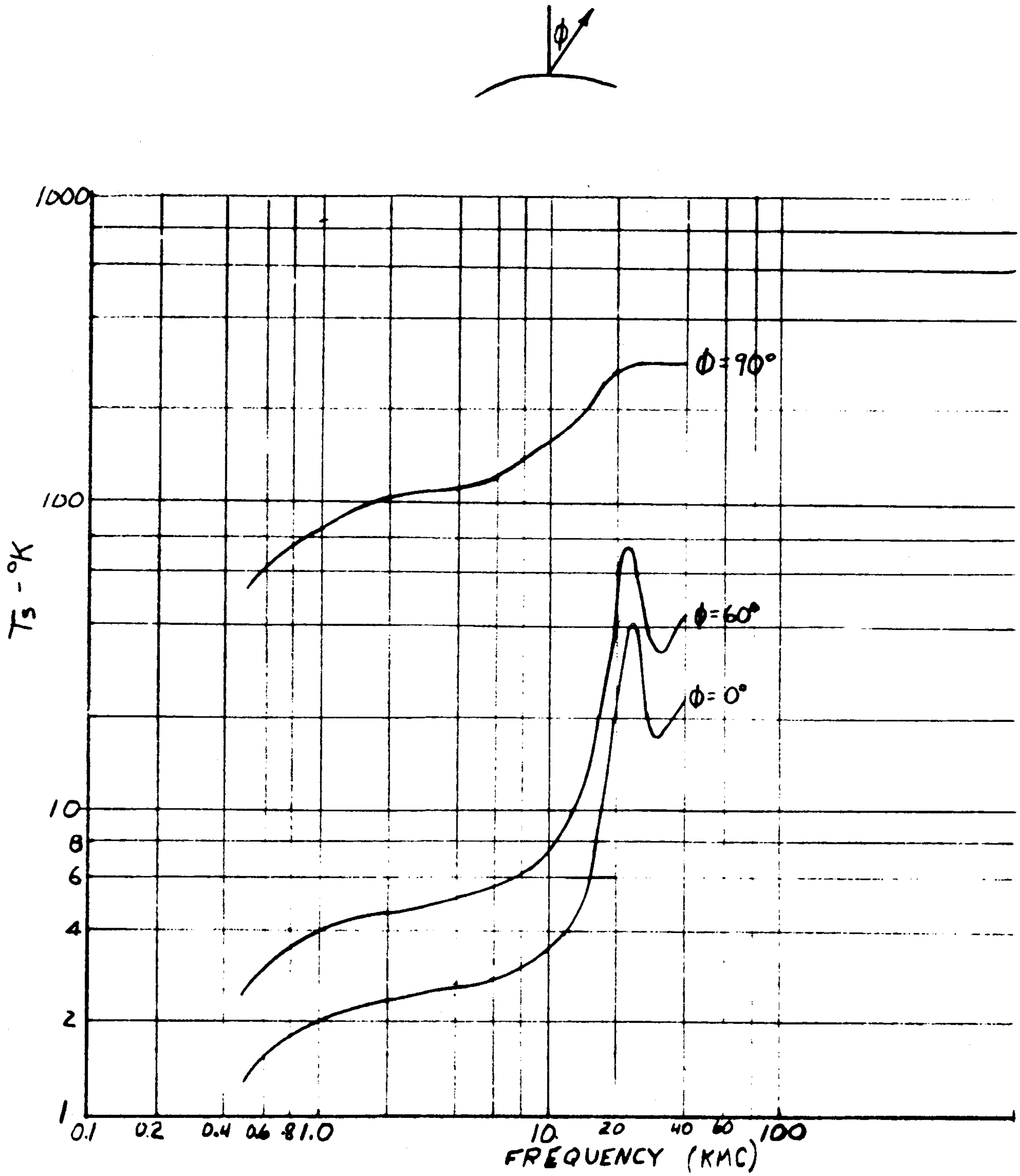
FIGURE 2-8



IRRADIANCE OF SKY.

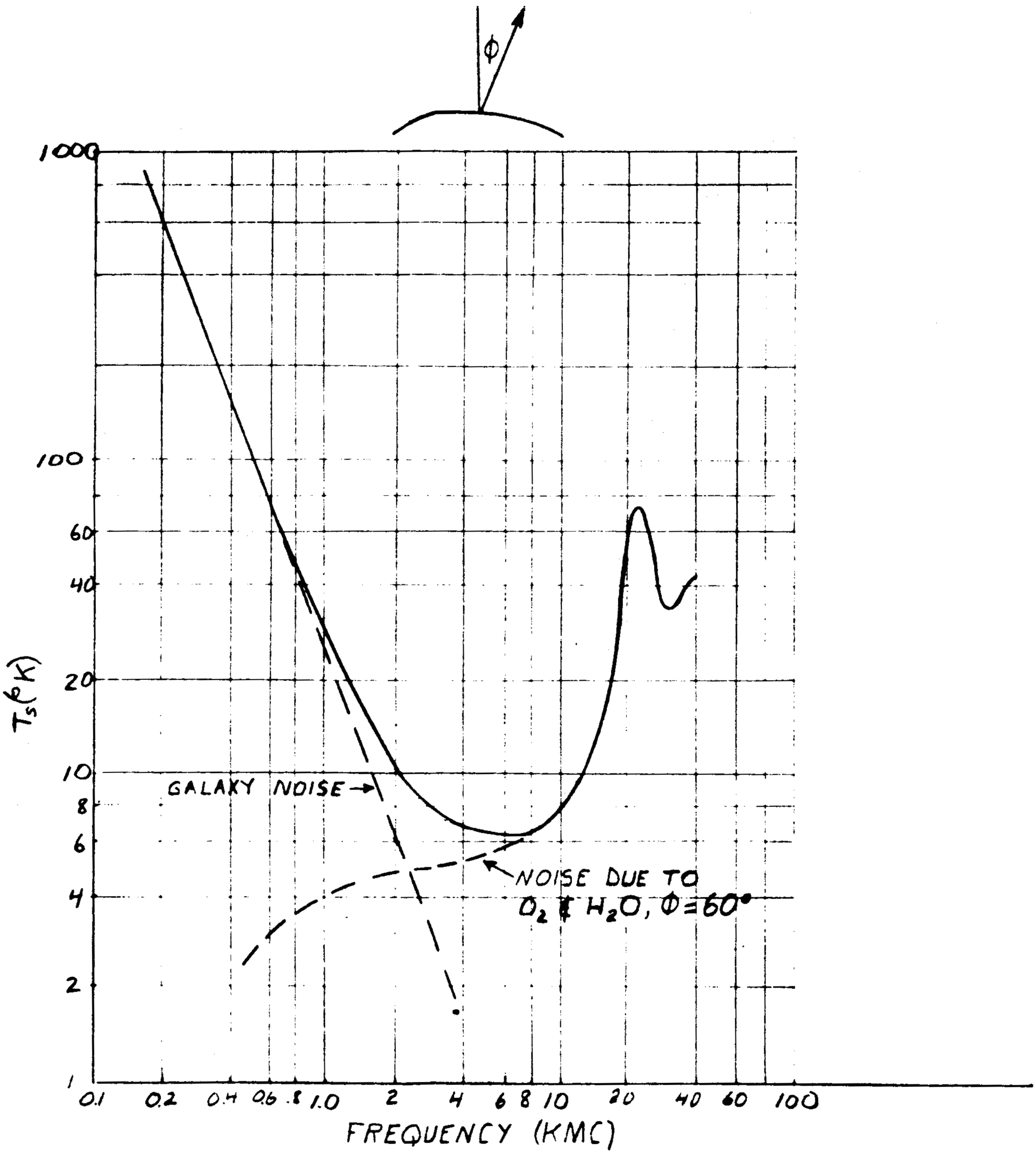
FIGURE 2-9

FIGURE 2-10
SKY NOISE TEMPERATURE*
(O_2 + H_2O)



* HOGG & MUMFORD, BELL TELEPHONE LABS., IN THE MICROWAVE JOURNAL MARCH 1960

FIGURE 2-11
SKY NOISE TEMPERATURE
(ALL SOURCES)



Refraction

A quantum of energy normally travels a straight path at a fixed velocity through a homogeneous medium absent of influencing force fields. If this bundle of energy enters a denser medium such as an atmosphere, the speed decreases a little. If the wave front enters the dense medium at an angle, portions slow up before others causing a change in direction of travel called refraction. The wave is 'bent' in the direction toward the normal of the denser medium. The amount of bending is proportional to the angle of entry with respect to the normal of the dense medium's surface. It is also proportional to the relative speeds in the two media which is a function of the density and is called the index of refraction (u). The angle of incidence (ϕ) and the angle of refraction (Θ) are related to u by Snell's law which says:

$$\frac{\sin \phi}{\sin \Theta} = \frac{n_1}{n_2}$$

where ϕ and n_2 are associated with one medium and Θ and n_1 are related to the other medium.

When the atmosphere is the dense medium, the bending is called the atmospheric refraction. The effect is to make the object in space appear higher than it actually is. Figure 2-12 shows a plot of refraction as a function of elevation angle. At the zenith there is no refraction but at the horizon it is as high as 34.5 minutes. The curve is for sea level altitude; for increased heights there is less atmosphere and the refraction decreases.

For a simplified communication link the angle may be limited to a minimum of 15°, but if a large compensation angle is tolerable, reasonably accurate apparent position of a space vehicle can be obtained down to about 2° elevation angle where the refraction becomes erratic.

There are many irregularities that influence the refraction. An example might be the low altitude turbulence that precedes or follows a storm. Other factors are: time of day, temperature inversion layer, large surface to air temperature differential, stratified air following long periods of no wind, ice winds across tropical lands, cold rivers runing into seas, sudden air temperature or pressure changes, change in humidity, azimuth angle at some latitudes. color of vehicle (red has been 4 times as much dispersion at the horizon as does blue), and irradiation (contrasting brightness objects apparent size growth). The parallax angle should be considered for vehicles reasonably close to the earth. Most of these are predictable and therefore correctable, while others are minor. Tables are available for correction of some factors like temperature and atmospheric pressure.

Image Motion

The turbulence of the atmosphere causes the apparent space vehicle to move around in a short random path. The amount of motion (maximum deflection) varies from time to time and from place to place. Adjacent to the sea and on high snowcapped mountains, where turbulent atmospheric conditions predominate, viewing is worse than on southern latitude peaks such as Mount Wilson, California.

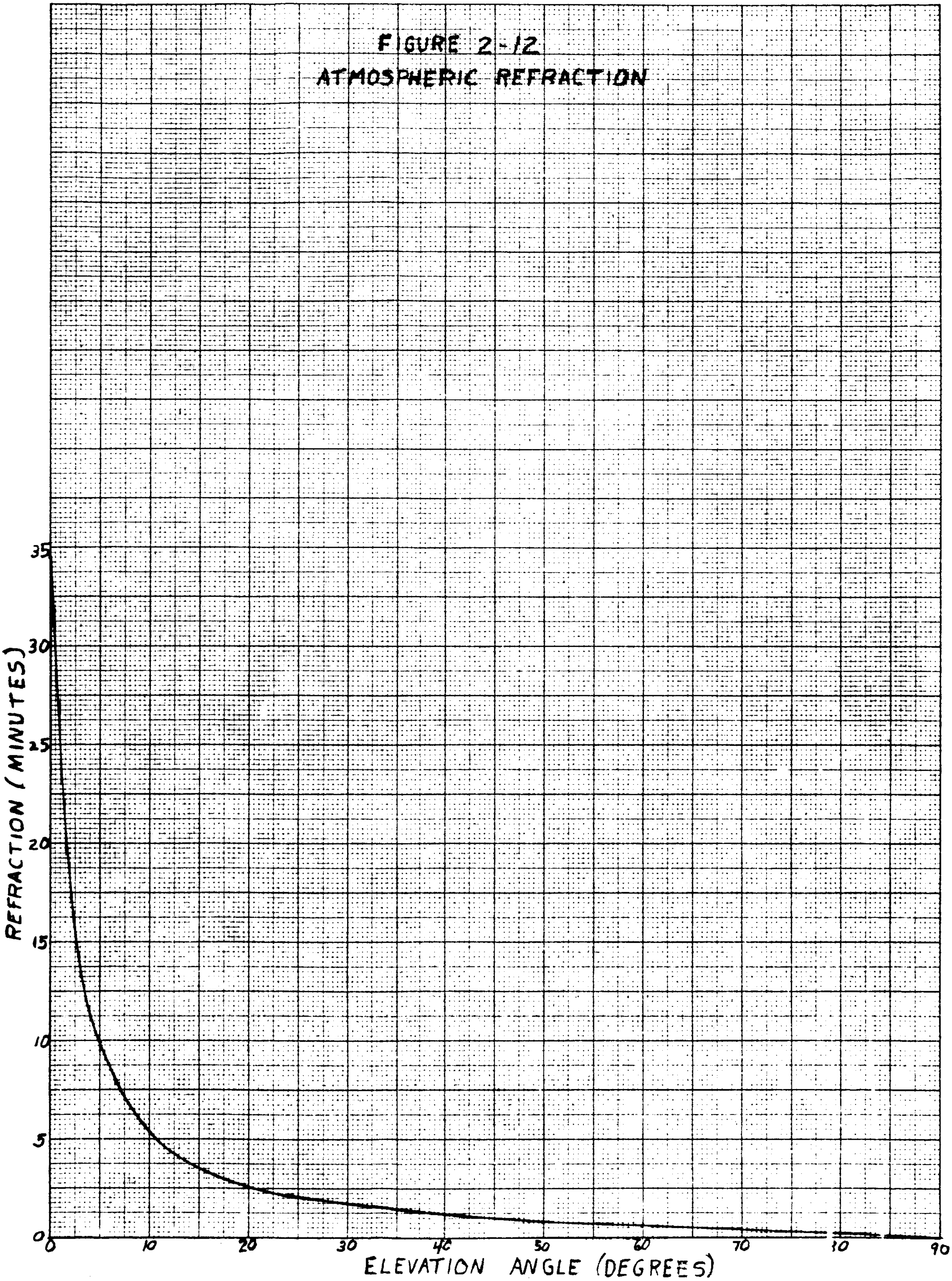


FIGURE 2-12
ATMOSPHERIC REFRACTION
REFRACTION (MINUTES)
35
30
25
20
15
10
5
0
0
10
20
30
40
50
60
70
80
90
ELEVATION ANGLE (DEGREES)

These random fluctuations in the direction of the light are dependent upon the size of the aperture of the receiver. With a small aperture only a small, narrow, almost parallel bundle of light enters the aperture whose direction varies with the turbulent atmosphere. This causes an apparent total displacement of the image. As the aperture size is increased the image begins to blue slightly and appears somewhat steadier. Further increases in aperture size result in a blurred image, but steady. The size of the blurred image is about the same size of the small aperture image motion limits. This is the result of the larger aperture capturing the non-parallel light rays simultaneously that enter the small aperture as a function of time, resulting in a smeared but somewhat larger image.

Tatarski* has shown that the mean square fluctuations of the angle of arrival ($\bar{a}^2$) of the light through the atmosphere is proportional to the secant of the zenith distance (Θ) of the light

$$\bar{a}^2 = A^2 \sec \Theta \qquad (1)$$

A is a constant depending on the meterological conditions in the order of a few tenths of an angular second. Figure 2-13 shows a plot of Equation 1.

It has been found that the fluctuations in angle of arrival are principally dependent on the lower layer of the atmosphere. There is a coodination of frequency and wind velocity, strong winds correspond to higher frequency.

Figure 2-14 shows a plot of image motion vs. elevation angle for good, average and poor seeing conditions. Figure 2-15 shows a representative plot of image motion vs. time.**

Pulsations

This results in an apparent change of size of the vehicle due to the turbulent atmosphere taking a momentary lense shape causing either an increase or decrease in magnification giving a change in image size. These variations may occur with a size ratio of at least 2 to 1.

Scintillation

This is a result of the atmosphere focusing and defocusing the image of the vehicle's light and appears as a 'twinkle' in intensity. The amount of twinkling is a function of the zenith angle. As the zenith angle gets larger, the high frequency fluctuations decrease and the low frequency components become more pronounced.

Scintillation corresponds to light and dark patches on the surface of receiver which are about ten centimeters across. These patches move across the surface causing intensity variations. The r.m s. amplitude is larger

*Tatarski, "Wave Propagation in a Turbulent Medium"

**Private conversation with A.H. Mikesell of the Naval Observatory by W.E. Horn, Westinghouse Electric Company; Space Optics Lecture Notes, UCLA, 1962.

FIGURE 2-13

QUIVERING

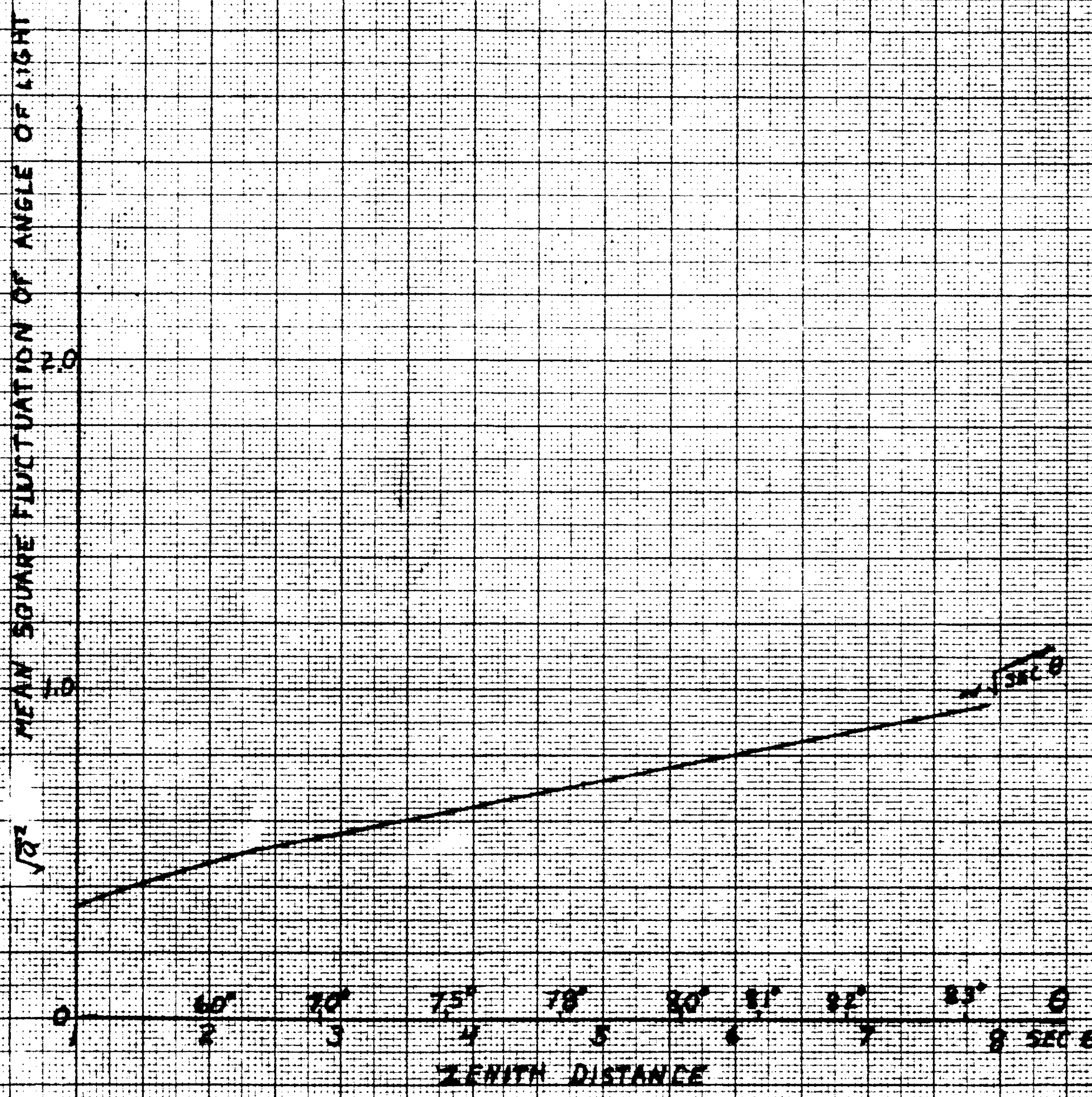


FIGURE 2-14

IMAGE MOTION vs ELEVATION ANGLE

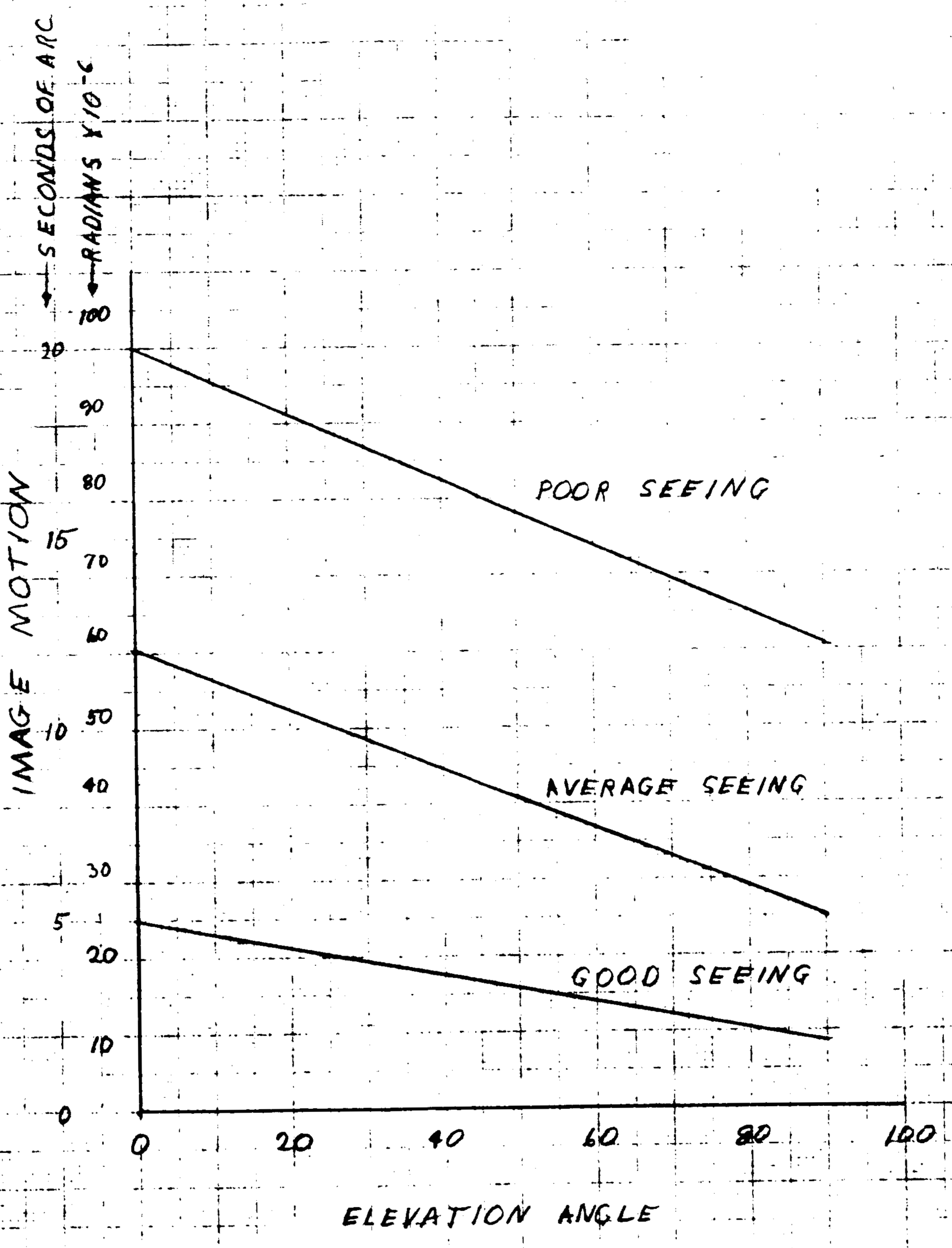
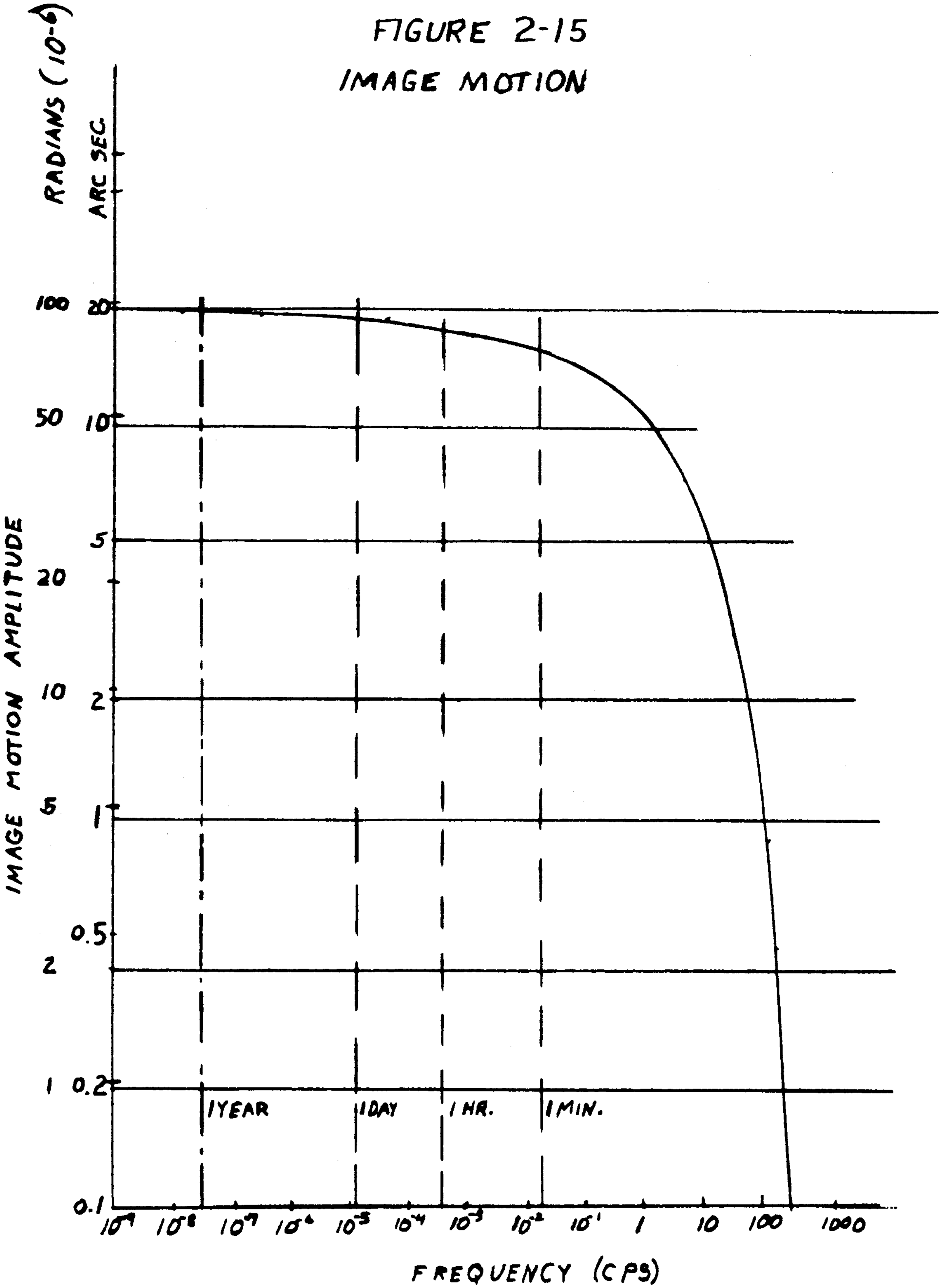


FIGURE 2-15

IMAGE MOTION



for small aperture receivers. Experiments (Protheroe 1955) have found the mean value of the scintillation is about 40 percent of the mean intensity for a 2.5 cm. aperture near zenith at right. Larger aperture fluctuations are much less, in the order of 5 percent for 30 cm objective but varies over a large range.

The number of patches on the objective is proportional to the square of the aperture radius $(R_2)^2$. The fluctuations of the integrated intensity from its mean value varies as the square root of the number of patches seen. The time average illumination is proportional to the area squared $(A_2)^2$. Then the ratio of the fluctuation to mean illumination varies as $1/R_2$. When $R_2 > 2\ (\Delta r)_o$ the following approximation holds

$$\frac{I}{IDC}^{1/2} = \sqrt{2/\pi} \quad \frac{(\Delta r)_o h}{R_2\ h_o}$$

where: $(\Delta r)_o$ = 2 cm (approximately)

I = mean-square fluctuation in intensity of light received through a circular aperture of radius R_2

IDC = time average intensity

h_o = mean illumination of aperture per unit area

h = mean square amplitude of intensity fluctuation in the pattern

This is good for at least the range $1.25\ \text{cm} < R_2 < 16\ \text{cm}$.

Figure 2-16 shows the twinkling as a function of the diameter of the receiving aperture. It can be seen that increases in aperture diameter beyond the diameter of the light and dark patches results in little improvement.

The lower layers of the atmosphere have little effect on the twinkling, i.e. scintillation appears to be a function of the higher atmospheric layers.

The frequency of the twinkling is a function of the zenith distance. The curve in Figure 2-17 shows a decrease in frequency with increased angle.

In searching, acquiring and tracking the space vehicle from a ground based station, small beam angles should be avoided where possible due to the complex and often unpredictable atmospheric effects. Large beam angles are not necessary (and undesirable from background noise point of view) since most of the disturbance factors of the atmosphere are very small and predictable for compensation. Low elevation angles should be avoided if a narrow beam is found necessary since most refraction effects are found here. High altitude stations are preferred in general due to the refraction improvement even though there is no improvement in the scintillation effects.

This atmospheric distortion study is based on a space to earth link. The earth to space system can be made equally as good with the proper selection of optics.

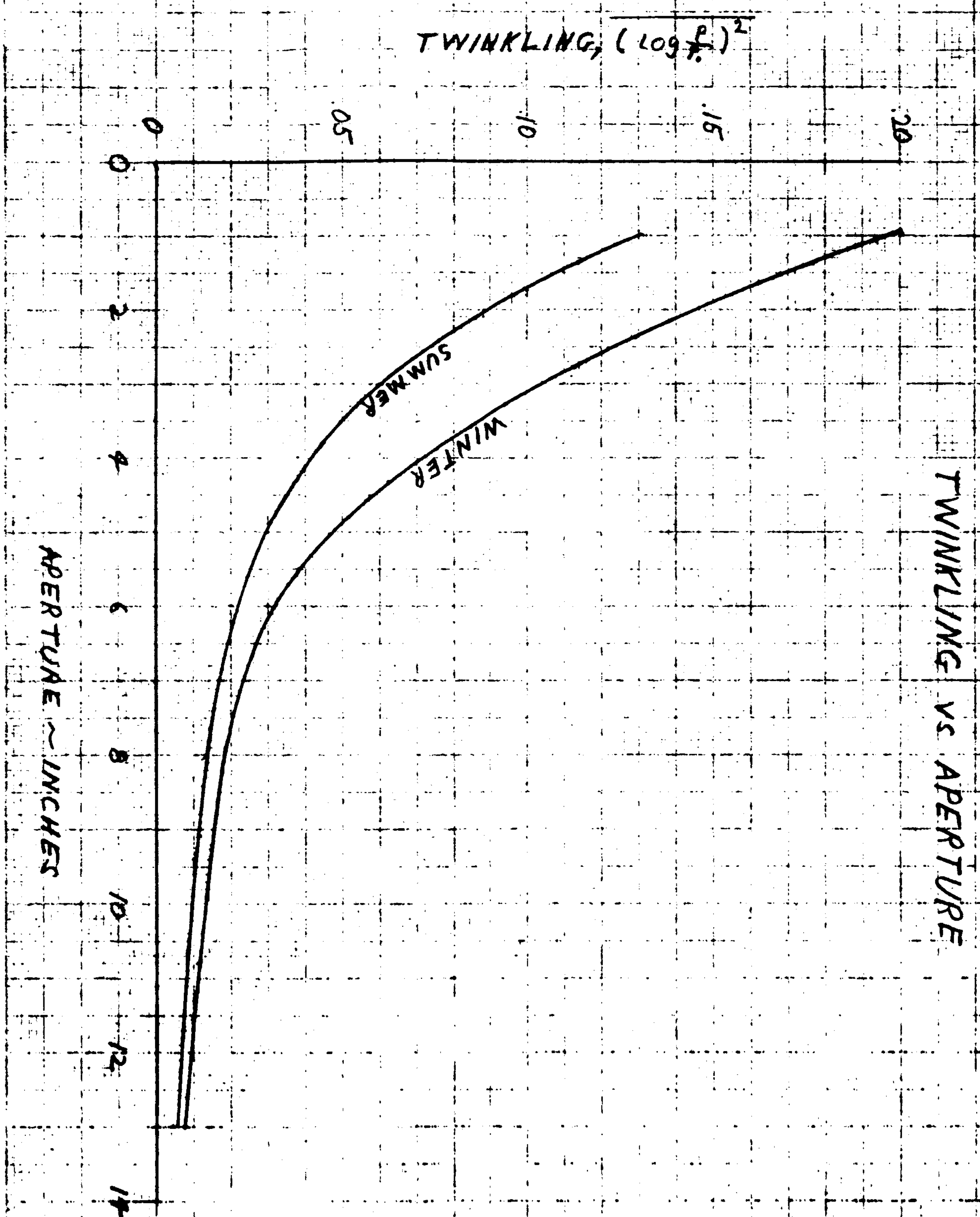
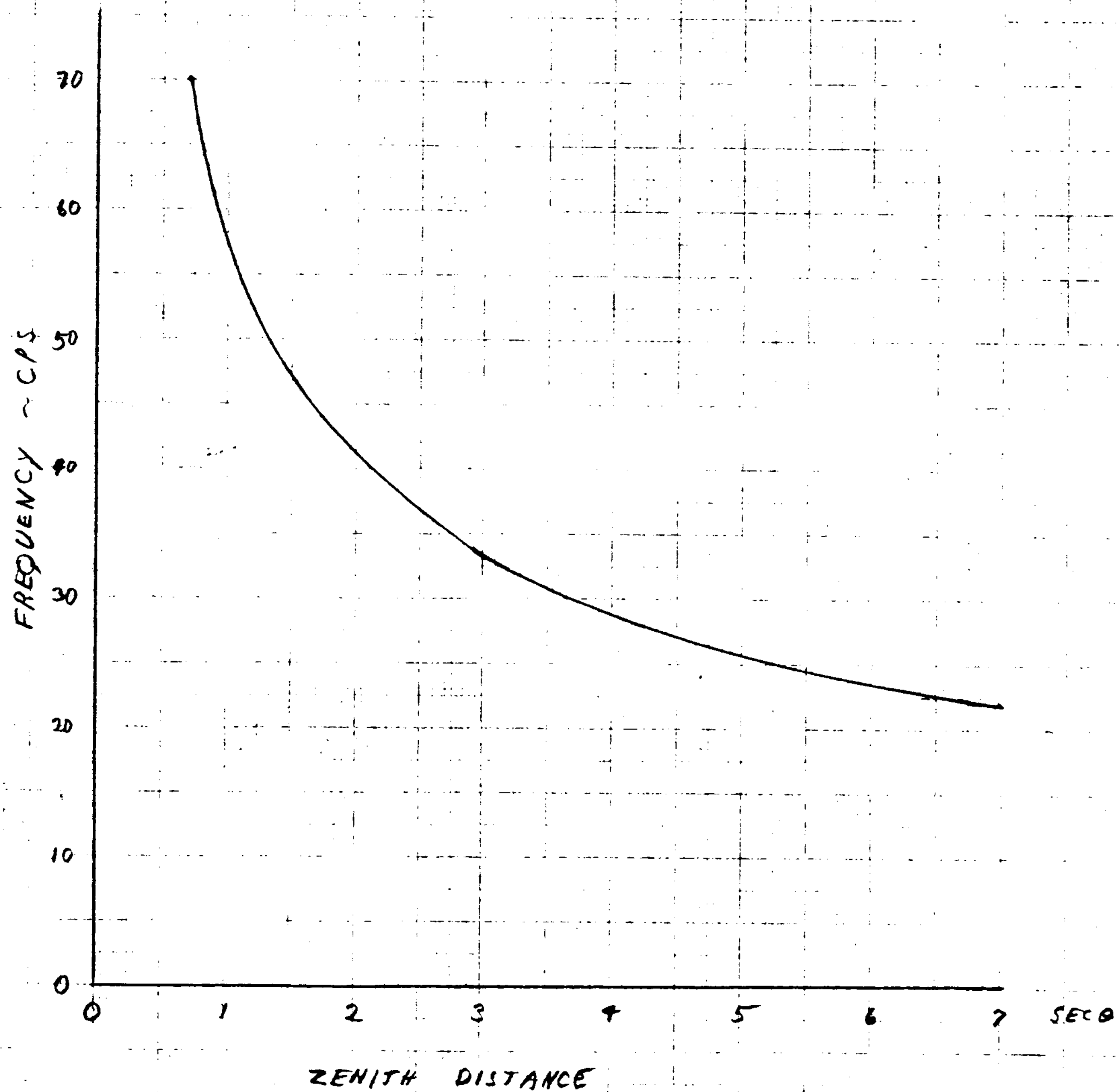

TWINKLING VS APERTURE
TWINKLING, $\overline{(\log \frac{I}{I_0})^2}$
0
.05
.10
.15
.20
0
2
4
6
8
10
12
14
SUMMER
WINTER
APERTURE ~ INCHES

FIGURE-2-16

FIGURE 2-17
TWINKLING FREQUENCY vs ZENITH DISTANCE



System Noise-Bandwidth Comparison

Figure 2-18 shows the noise in watts as a function of the information bandwidth in kilocycles for frequencies of five and 50 gigacycles and optical wavelength of 0.6943 and 2.36 microns.

The radio frequency noise was found by summing the effective filter bandwidth noise and the signal noise in the information bandwidth.

For the optical frequencies, a similar method was used but the noise power within the filter bandwidth was not significant.

For the 5 KMC case two values are given, the difference being in the assumed internal receiver noise. A temperature of 20°K was assumed for the worst case while the optimistic value assumed was 10°K. The optical bandwidth is given by the equation:

$$B = \frac{C\Delta\lambda}{\lambda^2}$$

where c = velocity of light, 3×10^8 m/sec.

λ = wavelength at frequency selected in meters.

B = bandwidth in cycles per second.

This gives bandwidths of 270 and 3100 cps for 2.36 micron and 0.6943 micron respectively, assuming a filter passband, $\Delta\lambda$, of 1A°.

The total noise is given by the equation:

$$N_\lambda = kT_e\, B_f + h\nu B_i$$

where K = Boltzmanns constant 1.38×10^{-23} Joules/degree K

T_e = effective temperature (3° k for sky)

B_f = filter bandwidth (cps)

h = Planks constant 6.625 c 10^{-34} Joule-sec.

ν = c/λ (carrier frequency)

c = velocity of light 3×10^8 m/sec

λ = wavelength of carrier

B_i = information bandwidth, cps

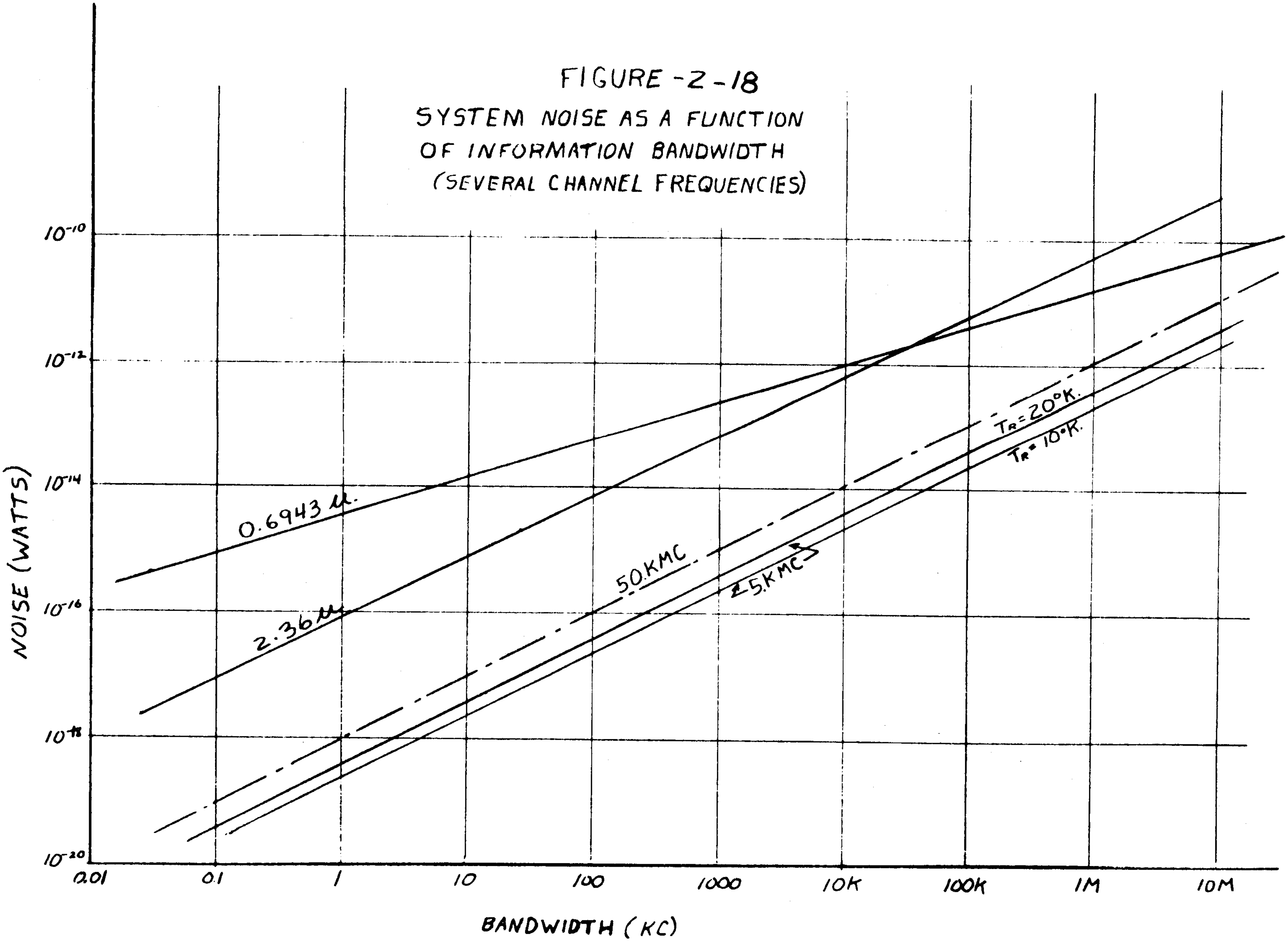
For the radio frequencies the total noise is given by the equation:

$$N_R = K\, T_e\, B_f + K\, T_r\, B_i$$

T_r = receiver temperature, °K.

FIGURE - 2 - 18

SYSTEM NOISE AS A FUNCTION OF INFORMATION BANDWIDTH (SEVERAL CHANNEL FREQUENCIES)



For the 5 gigacycle case the temperatue is composed of $1^{\circ}K$ galactic, $1^{\circ}K$ earth (from antenna side lobe), $5.2^{\circ}K$ sky ($H_2O \notin O_2$), and receiver noise of $20^{\circ}K$ and $10^{\circ}K$.

For the 50 gigacycle frequency the temperature is made up of $0^{\circ}K$ galactic, $1^{\circ}K$ earth (side lobe of antenna), $54^{\circ}K$ sky, and receiver temperature between 25° and 50° K. The two 50 gigacyle cases are plotted as one because of negligible separation.

The background noise is given for average conditions. There will be times in long life missions when the background noise will be much greater due to the near accultation of a particularly strong source of discrete noise by the vehicle. The peak intensities which result will be of short duration. The effects can be predicted well in advance and the necessary allowances can be made.

Such refinements as the effects of discrete source spatial distribution, Faraday rotation, etc. will be considered in the more complete analysis which will follow.

3.0 OPTICAL MASER TECHNOLOGY

With the development of optical maser oscillators, it is now possible to generate coherent radiation of a large number of optical frequencies at considerable power levels. Maser oscillations have been obtained in many different types of materials. The most frequently used have been of the solid state and gaseous type. Maser oscillations have also been obtained in glasses, optical fibers, liquids, organic materials and semiconductors.

3.1 SOLID STATE OPTICAL MASERS

Solid state lasers are usually excited by broad-band absorption of optical frequency radiation. A fast non-radiative transition then populates sharp fluorescence levels; and when a sufficient population of excited states is obtained, stimulated emission takes place with the subsequent emission of coherent narrow beam radiation.

When the terminal level of the radiative transition is the ground state, the optical maser is called a three-level system. Ruby is an example of a three-level maser. In four-level masers, the terminal level lies above the ground state. Almost all solid state lasers are of the four-level type. To obtain maser oscillation in a three-level system, one must have a slight inversion of the excited and ground states, and to maintain the inversion, at least as much power must be supplied to the cavity as is lost by spontaneous decay of the upper level and the non-radiative transition. The power emitted by spontaneous decay is proportional to the number of excited states and, since in a three-level system the number of excited states required for oscillation is more than half the number of dope-ions, it takes a large input power to maintain the oscillation.

In a four level system when the terminal level is far enough above the ground state, its population will be negligible. It then requires a correspondingly smaller population in the excited state to obtain maser oscillation. The power lost to spontaneous decay will then be less with the consequence that the threshold for oscillation can be relatively small. Other factors such as narrow absorption band, low quantum efficiency and scattering of radiation also influence the threshold for maser oscillation.

3.2 PULSE OPERATION

The power output of solid state lasers is usually obtained in the form of pulses. In this type of operation, the laser is usually irradiated for a short period of time with a broad-band optical source. In the experiments with ruby performed by Maiman, et al (Reference 1), the excitation light from a flash lamp is appreciable for times of the order of millisecond. The stimulated emission lasts for some fraction of that time. The emitted pulse of radiation is not smooth; it consists of spikes or oscillations occuring with a frequency that depends on the instantaneous intensity of the flash tube light. The amplitude of the spikes is somewhat erratic, and the average frequency of the spikes is about 2×10^6 c/sec and the length of the whole pulse is about 0.5 milliseconds. Hence there are about two or three hundred oscillations in a single pulse. The largest peak power obtained in the experiments was 5 kilowatts with an energy of nearly a joule in the pulse.

Divalent and trivalent rare earths in suitable host materials generally satisfy the characteristics necessary for maser action. Trivalent Uranium in several different hosts have also been made to laser. Table I is a partial summary of solid state materials which have produced maser oscillations. Some of the characteristics of their operation are shown. The pulsed operation of the four-level systems is essentially the same as that described for ruby. The four-level masers tend to be more sensitive to temperature, since to obtain efficient operation the terminal level often has to be depopulated by cooling. As in ruby, the output consists of spikes in the main pulse. These oscillations often appear strongly damped in contrast to ruby where no damping has been observed. In one case ($CaF_2 : Dy^{++}$) there appears to have been critical damping of the oscillations as they were not detected (Reference 2). Usually the frequency of the oscillations is fairly constant with some fluctuations of the amplitude. A pulse that consists of very regular damped oscillations has been observed (Reference 3) in $CaWO_4 : Nd^{++}$, but because of the narrow absorption band this laser does not seem suited for high power operation. Threshold energy for pulse operation is generally much lower than the 800 joule threshold in ruby. At low temperatures, threshold energies of the order of a few joules have been observed in several different maser systems (see Table I).

The threshold energy is sensitive to changes in temperature. The dependence of threshold for maser action in $CaF_2 : U^{3+}$ has been measured by Boyd, et al (Reference 4). The flash lamp energy required to obtain maser oscillation was: 20 joules at 20°K, 3.78 joules at 77°K, 4.35 joules at 90°K, and about 300°K. Temperature dependence of the threshold energy has also been observed for most of the other materials.

The non-radiative transition results in absorption of energy by the crystal lattice, and hence in continuous high power operation there will be a large amount of energy transferred to the crystal lattice. Maintaining constant temperature under these conditions presents a difficult cooling problem. Heat transfer from the maser material will probably be of practical importance in attaining high power repetitive pulsing in solid state materials.

3.3 GIANT PULSE

In normal pulsed operation, oscillations begin as soon as a critical inversion is achieved, that is, as soon as the single pass gain exceeds the single pass loss. Oscillation may be postponed by making reflection losses very large and if the ruby is strongly excited a high inversion can be established. A Kerr cell switching technique has been used to decrease the

TABLE I. Properties of Solid State Lasers

Material	Type	Wavelength (Microns)	Threshold Energy to Flash Pump (Joules)	Temperature (Deg Kelvin)	Remarks	Reference
$Al_2 : Cr^{3+}$	3-level	0.6943	695	77	Continuous operation 77°K, 850 watts Flash power threshold	10, 8
$Ca\ F_2 : U^{3+}$	4-level	2.613	2.0 3.78 4.35 1200	20 77 90 300	Continuous operation 77°K, 1200 watts Threshold flash power	4
$Ca\ F_2 : Sm^{2+}$	4-level	0.708	5	20		
$Ca\ F_2 : Dy^{2+}$	4-level	2.36	0.1 1	4 77	Continuous operation 27°K, 0.5 watts output, 50 watt threshold flash power	2, 9
$Ca\ F_2 : Tm^{2+}$	3-level 4-level	1.116 1.189	50 50	4.2 4.2		22
$Ca\ F_2 : Nd^{3+}$	4-level	1.046	80	77		7
$Sr\ F_2 : U^{3+}$	4-level	2.407	8 32 38	~20 77 90	No maser oscillation at 300°K with 2000 J flash energy	23
$Ca\ WO_4 : Nd^{3+}$	4-level	1.063	3 5	77 300	Continuous operation ~85°K, 1300 watts flash power	3
$Ca\ WO_4 : Pr^{3+}$	4-level	1.0468	70	77		2
$Ca\ WO_4 : Tm^{3+}$	4-level	1.911	125	77		24
$Ca\ WO_4 : Ho^{3+}$	4-level	2.046	300	77		2
$Ca\ WO_4 : Er^{3+}$	3-level	1.612	800	77		2
$Sr\ Mo\ O_4 : Nd^{3+}$	4-level	1.064	42 125	77 300		25
$Sr\ Mo\ O_4 : Pr^{3+}$	4-level	1.047	~70	77		
$La\ F_3 : Nd^{3+}$	4-level 4-level	1.063 1.0399	93 75	77 77		

cavity loss suddenly. One then has inversion far above threshold with the consequence that the energy in the cavity is dumped in a very short high power pulse. McClung and Hellwarth (Reference 5) have obtained peak output powers of 600 kilowatts with a pulse duration of 12 μsec. More recently, Woodbury (Reference 6) using a slightly different arrangement has measured peak powers of 20 megawatts of pulse duration 7×10^{-9} sec.

In principle, one can control the length and power in a single pulse of this type. The power out would be roughly inversely proportional to the pulse duration. Of course, there is a limit to the peak power obtainable, which is set by the maximum energy that can be stored in the ruby and the minimum time it takes to dump it. This time cannot be less than the time it takes a photon to traverse the length of the cavity several times.

Ruby is especially well suited to the giant pulse mode of operation because of the relatively long lifetime of the fluorescence level.

3.4 CONTINUOUS OPERATION

In continuous operation of four-level solid state materials, the oscillations that are characteristic of the pulsed mode are damped out in times less than a few milliseconds, or they have not been observed at all because of inadequate time resolution of the detecting device. This is in contrast to ruby where the oscillations persist with a fairly regular frequency and a large slightly erratic amplitude. The characteristics of the oscillations are similar to those observed in the pulse mode of operation.

Continuous power output has been obtained with several different maser materials. The system $CaF_2 : U^{3+}$ has operated continuously at 77°K (Reference 4) with output power of 10 μwatts. Threshold for continuous oscillation is 1200 watts and maser action occurs at a wavelength of 2.613.

Trivalent Neodymium in host material $CaWO_4$ has lasered continuously at 77°K with 1300 watts flash tube power (Reference 7) and output of 1 milliwatt at 1.065 μ. The system $CaF_2 : Dy^{++}$ has also been made to oscillate continuously (Reference 2). In the first reported operation, the output was about 2 milliwatts at 2.45 μ. At 27°K the threshold for continuous operation was 600 watts electrical input to the lamp.

Continuous operation has also been attained in a ruby optical maser (Reference 8) with the maser oscillation at 0.6943 μ. The threshold for oscillation at 77°K was 850 watts supplied to a short arc high-pressure mercury lamp. At an input power 950 watts, the maser beam produced 4 milliwatts of power, and as mentioned above consisted of undamped oscillations.

It has been reported recently that threshold for continuous operation with $CaF_2 : Dy^{++}$ has been reduced to 50 watts using a tungsten lamp as the pump (Reference 9). Using a 1 kilowatt tungsten lamp, continuous power of about 1/2 watt has been obtained. The power is concentrated in a single mode when operated at liquid Ne temperature and power efficiency with respect to energy absorbed by the material of about 1 percent. Considerably higher powers are expected with improved cooling and optimized crystal geometry. It is clear that $Ca\ F_2 : Dy^{++}$ is presently one of the most promising materials for high power continuous output.

Ruby is another material that at least theoretically should be capable of high continuous power output (Reference 10). The development of a 10 watt continuous ruby laser has been proposed, and theoretical considerations indicate that this should be possible without any radically new technological developments. Efficiencies of about 1 percent are anticipated. So far, relatively little effort has gone into obtaining high efficiency, high continuous power, or high power repetitive pulsing. To our knowledge, efficiencies reported in the literature are less than 1 percent and are usually less than 0.1 percent. There does not appear to be a basic limitation that would prevent substantial increases in efficiency in the normal course of the development of laser technology. Townes (Reference 11) has speculated that efficiencies of 10 or 20 percent are possible.

Related to the problem of efficiency is the production of high power, or more precisely high continuous or quasi-continuous power. As discussed above, it is presently possible to obtain very high power pulses of short duration. However, the rate at which these pulses may be repeated is presently limited by the power capabilities of the excitation source and by heating of the ruby and optical elements in the system.

The attainment of high power repetitive pulses or continuous power output depends, among other things, on the development of higher efficiencies, adequate cooling techniques and improved excitation sources. It seems that with an effort in this direction continuous power from 1 to 10 watts and repetitive pulsed output of, say, 10 to 100 watts average power will be possible in a few years or less.

3.5 SPECTRAL CHARACTERISTICS

Optical maser oscillations have been obtained in the range 0.6943 to 2.613 μ (see Table I). The output exhibits spacial and time coherence with beam angles that are typically about 10^{-2} radians. There is presently not much information in the literature about the line width and frequency stability of the output of solid state materials with the exception of ruby.

In ruby the spectral width of the light output appears to be set by the 0.5 μsec interval between spikes as the measured bandwidth of the emission from a single spike is about 2 megacycles per second.

When the spectral distribution of the radiation from a number of spikes was measured, a bandwidth of 20 megacycles per second was obtained, which showed that there was no coherence between successive pikes. It has been observed that the ruby oscillates simultaneously in a number of axial modes

(Reference (13). There is evidence of spacial coherence over the end face of the ruby of the order of 100 wavelengths (Reference 14).

The frequency of the ruby line is temperature dependent which indicates thermal tuning in possible. Measurements of the temperature dependence of the frequency of the R_1 ruby line show that the change of wavelength with temperature is 0.065 Å/deg (Reference 15). Because the spectral width is of this order, good temperature control is necessary for frequency stability.

3.6 GASEOUS OPTICAL MASERS

Maser oscillations of frequencies ranging from the visible (0.63 μ) to the middle infrared (12 μ) have been obtained in gaseous materials. So far, maser action has been obtained in 10 different gaseous systems (see Table II). A considerable amount of theoretical and experimental work has gone into the study of the He-Ne gas system (Reference 16). The oscillator consists of a Fabry-Perot interferometer about a meter long, and population inversion is achieved by exciting helium atoms to a metastable state in an electrical discharge. The helium atoms transfer the excitation energy to the neon gas by collisions. Under suitable conditions a stimulated transition of the excited neon atoms to a lower level takes place to give the maser oscillation.

The output of gaseous lasers is characterized by extremely monochromatic, narrow beam, continuous radiation. Inherent line widths of 2 cps have been obtained in a He-Ne system (Reference 17). Frequency stability has been found to be 2 parts in 10^9 over 100 second time intervals. It is expected that it will be possible to obtain a high degree of long term frequency stability in gaseous lasers.

The power output of most gas lasers has been of the order of milliwatts. As in the solid materials, relatively little effort has been made to obtain high power outputs. In the He-Ne system 15 mwatts was obtained in a single line with an estimated power dissipation of 50 watts. Saturation occurs at about 75 watts and additional power input does not increase the output power in the beam. Bennett (Reference 18) suggests that through the use of mode suppression techniques in long interferometers, through the use of cooling techniques in multiple tube structures or through the use of power amplifiers that a sizeable fraction of a watt might eventually be obtained.

Gas lasers, for reasons that are related to their low density, do not have the potential for high power pulsed operation that exists in solid state material.

Some reported characteristics of optical masers are given in Table III. We may not have the most recent capabilities of optical masers. For example, gas lasers may already be able to produce powers greater than the 10 mwatts listed in the table.

TABLE II. Summary of Optical Maser Transitions and Beam Power

Gas	Wavelength (microns)	Continuous Power (mW per beam)	Reference (first work)
Helium-neon	0.6328	4	26
	1.0798		
	1.0845		
	1.1143		
	1.1177		
	1.1390		
	1.1409		
	1.1523	20	16
	1.1601		
	1.1614	1	16
	1.1767		
	1.1985		
	1.2066		
	1.5231	3	27
	3.3913	10	28
Cesium	7.1821	0.025	29
Neon-oxygen	0.84462	1	30
Argon-oxygen	0.84462	1	30
Helium	2.0603	3	31
Neon	1.1523	1	32
	2.1019	1	31
	5.40		33
Argon	1.6180		
	1.6941	0.5	31
	1.793		
	2.0616	1	31
Krypton	1.6900		
	1.6936		
	1.7843		
	1.8185		
	1.9211		
	2.1165	1	31
	2.1902	1	31
	2.5234		
Xenon	2.0261	5	31
	5.5738		33

TABLE II (cont). Summary of Optical Maser Transitions and Beam Power

Gas	Wavelength (microns)	Continuous Power (mW per beam)	Reference (first work)
Helium-xenon	2.0261	10	31
	2.3193		33
	2.6269		
	2.6511		
	3.1069		
	3.3667		
	3.5070		
	3.6788		
	3.6849		
	3.8940		
	3.9955		
	5.5738		
	7.3147		
	9.0040		
	9.7002		
	12.263		
	12.913		

TABLE III. Present Power Performance

Pulse Operation

Material	Threshold energy to excitation source	Peak pulse power	Line width	Beam angle	Remarks
Ruby	695 J	3 Kw	2 mc/sec	0.01	Each pulse consists of undamped oscillations. The pulse length is controlled by the duration of excitation. Repetitive pulsing at rates of the order of 1/min.
Ruby (Giant pulse)		20 KW-20 mW	2 mc/sec	0.01	It is possible to control the pulse length. Pulses as short as 7×10^{-9} sec have been obtained.
Four Level Systems	5 J	--	--	0.01	Oscillations in the pulse are damped. Threshold energies range from 1 to 800 J. Cooling is usually required to depopulate the terminal level.

Continuous Operation

Material	Threshold power to excitation source	Power in laser beam	Line width	Frequency stability	Beam angle	Remarks
Gaseous	25 W	~10 mW	2 c/sec	0.5 mc/sec	2×10^{-4} rad	Output frequency is sensitive to acoustic vibration and temperature.
Solid state	50 W	0.5 W	--	--	10^{-2} rad	These numbers are for $CaF_2 : Dy^{++}$. Relatively small amplitude oscillations are present in the output. Ruby seems to be capable of similar output.

Table IV gives anticipated power performance. These numbers do not seem to be unrealistic in view of estimates based on existing technology made by current workers in the field.

3.7 OTHER MASER MATERIALS

Laser action has been obtained in a semiconductor, in Nd^{3+}-doped glass and in liquid and organic materials. These laser materials have been investigated to a much lesser extent than the solid state and gaseous materials.

The Ga As diode laser (References 19 and 20) is particularly interesting because it realizes the direct conversion of electrical energy to coherent radiation. The emission is in the infrared with measured spectral width of 15°A. The power out is proportional to the input electrical current when electrical current is applied in the form of pulses of 5 to 20 μsec duration with the diode immersed in liquid nitrogen.

Maser action at 1.06 μ in Nd^{3+}-doped glass has been obtained using clad fibers (Reference 21). The cladding results in a reduced number of modes of oscillation and can provide for high-Q surface wave modes at the optical interface between the core and the cladding of the drawn glass fiber.

TABLE IV. Future Power Performance

Operation	Material	Power per pulse	Pulse repetition rate	Average power	Efficiency
Pulse	Solid state	1-10 KW	$\sim$1/sec	10-100 watts	1-10 percent
Giant Pulse	Ruby	10 KW-100 MW	--	--	1-10 percent
Continuous	Solid state	--	--	--	1-10 percent
Continuous	Gaseous	--	--	$\sim$0.5 watts	1-10 percent

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4.0 OPTICAL DETECTOR TECHNOLOGY

Since the state of optical detector technology was considered to be more completely understood and less critical for the results of this study, it was decided to concentrate early on the Statistical Theory of Quantum Detection in order to resolve as quickly as possible some of the problems in interpretation of information capacity of optical beams. This section is a report on the results of that study thus far. It is intended to pursue this study in the next study phase as well as prepare an up-to-date survey and analysis of existing optical detectors.

4.1 THE THEORY OF THE TRANSMISSION OF INFORMATION BY OPTICAL MEANS

Even if no components or environments introduce noise in an optical communications system, such a system will still not be noise-free because of the nature of light itself. One may assign an information capacity to a specified optical communication system on the basis of photon fluctuations of the signal alone. Other sources of noise may further degrade this capacity, but it is of prime importance to understand this basic limitation. An additional photon noise input that is often not completely removable is the photon fluctuation due to a steady input of ambient light, such as that from the daytime sky. The theory of the information capacity of a beam of light under these conditions, subject to the restriction that the light is nondegenerate (incoherent), has been developed by Jones.[1]

Jones developes the concept of information efficiency I_t, given in bits per photon, and shows that this efficiency may be made as great as desired by increasing the significance of the arrival time of the photon or photons constituting a signal pulse. This is done by increasing the interpulse period and/or by decreasing the time uncertainty in the pulse arrival. Such a scheme would decrease the average transmitted power and hence reduce the information capacity C (bits per second) if one merely modulated the output of a continuous transmitter; however, since the giant-pulse laser and the hair-trigger-mode laser approximately maintain their average transmitted power in such circumstances, such modulation is quite practical for laser communication systems. In other words, the theoretical optimum probability for pulse transmission per pulse period is not $p = 1/e$ for such systems, but instead $p \rightarrow 0$ is better; the optimum value is a matter of practicality.

Jones' analysis included a calculation of the threshold and signal level needed to optimize I_t in the presence of ambient light for different values of p. In Table I, p is the probability that a "one" was transmitted during one pulse period (i.e., one pulse duration or gate period) of T seconds, A is the mean number of ambient photons received within T seconds, B is the optimum threshold setting in terms of photons per T, and M is the optimum

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(1) R.C. Jones, J. Opt. Soc. Am. 52. 493-501 (May 1962)

mean number of received signal photons per pulse, where the optima are taken to maximize the information efficiency I_t, in bits per photon. The data are valid with two important restrictions, namely that classical statistics are applicable to the photon count probabilities and that no other noise sources are present. Although these restrictions are not rigorously satisfied by the laser communication systems we are working on, the data given in the table are approximately correct for certain important types of such systems. However, for systems using lasers having high spectral purity (very narrow spectral lines) these data will often lead to overly optimistic predictions.

Table I. Conditions that maximize information efficiency I_t.

p	A	I_t bits/photon	R	M
0.5	0	1.0	1	0
0.5	0.5	0.33065	2	2.6
0.5	1.0	0.26325	3	3.75
0.5	10	0.11058	16	11.75
0.5	30	0.069315	39	18.6
0.1	0	3.32193	1	0
0.1	0.5	0.73298	3	3.6
0.1	1.0	0.58757	4	4.5
0.1	10	0.24608	18	13.0
0.1	30	0.15401	43	21.2
0.001	0	9.96578	1	0
0.001	0.5	1.28758	5	6.0
0.001	1.0	1.05594	6	7.0
0.001	10	0.46554	23	18.6
0.001	30	0.29558	51	30.0

Jones has considered the properties of radiation detectors from an information theory standpoint in two other papers [2] [3]. The second of these gives information efficiencies for the detection of symmetrically modulated light signals by several types of detectors. Although these results are less complete and significant than those given above, the data

(2) R. C. Jones, J. Opt. Soc. Am. 50, 1166-1170 (Dec. 1960)

(3) R. C. Jones, J. Opt. Soc. Am. 52, 1193-1200 (November 1962)

in Table II should be a helpful guide because they indicate the relative advantages of various detectors. It should be noted that the change $p \neq 0$ would generally result in information efficiencies greater than those given in Table II.

Table II. Information efficiency of various detectors for symmetric modulation.

Wavelength, millimicrons	Detector Type	I, bits/photon	Detector area, cm^2
400	1 P21 Phototube	0.1	1.0
510	Human Vision	7.2×10^{-3}	-
430	Royal-X Film	1.27×10^{-3}	10^{-4}
395	6849 Orthicon	2.0×10^{-5}	1.0
500	Heat Detector	1.65×10^{-8}	1.0

In addition to these tabulated data, relations are given that aid one in determining the effect of various types of detector noise on the information efficiency or capacity. Since these relations are not explicit expressions, each type of system must be analyzed separately. The problem of system optimization has yet to be fully studied.

In all the preceding analysis, it is to be understood that the light beam is not degenerate. The means for determining degeneracy will now be developed.

For interplanetary communication the transmitter and receiver will usually appear to each other as point objects, i.e., the angle subtended by the aperture of each as seen by the other will be much less than the diffraction limit of the observing aperture. Since there will therefore be no possibility spatially distinguishing the photons of the beam, such a beam may be said to be spatially degenerate. The degeneracy of the beam is then determined entirely from the number of photons n received within the coherence time ξ of the light.[4] The coherence time ξ is of the order of $(2\Delta\lambda)^{-1}\,\pi^{-1/2}$, where $\Delta\lambda$ is the frequency spread of the source in cps; if the pulse period T satisfies the relation $T \gg \xi$, this is the appropriate time, but as T approaches zero the value of ξ must also approach zero in order that $T \geq \xi$ may be satisfied. This relation expresses the well known result that modulation causes spectral broadening.

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(4) L. Mandel, Proc. Phys. Soc. 74, 233-243 (Sept. 1959)

The number of degrees of freedom or independent states is given by T/ξ. If the average number of photons per pulse period T is represented by $\bar{n}$, the average number of photons per state (the degeneracy parameter) is given by $\bar{n}\xi/T$. For nondegenerate light, $\bar{n}\xi/T$ = zero, and for fully degenerate light, $\bar{n}\xi/T = \bar{n}$. The theory of Jones is applicable when $\bar{n}\xi/T \ll 1$.

As an example, let us consider a multiple-giant-pulse ruby laser transmitter having a bandwidth of 0.5 Å and a pulse duration of 3×10^{-8} sec. Here $\Delta\lambda = 3.0 \times 10^{10}$ cps and $T = 3 \times 10^{-8}$ sec. We find that $\xi =$ 9.4×10^{-12} sec and hence that $T/\xi = 320$. Since $\bar{n}\xi/T = 0.1$ for $\bar{n} = 32$, the beam may be considered nondegenerate for most purposes if $\bar{n} \lesssim 32$. Since the photons that are not detected have negligible effect, $\bar{n}$ may be considered to be a photoelectron count; such a signal is more than adequate for operation with ambient radiation from the daylight sky.

Many laser systems will not be even approximately nondegenerate. Moreover, the dynamics of internally controlled lasers may prove to be complex. Starting points for a study of noise in such laser systems are the work of Mandel [4] and also a paper by Shimoda, Takahasi, and Townes [5]. Mandel gives the probability distribution of photoelectrons for any degreee of degeneracy of a beam of light with rectangular spectral line shape, whereas the latter paper is concerned with noise in maser amplifiers and may provide tools for analysis of noise in feedback-controlled pulsed lasers.

In summary, the study to date indicates that the most efficient system is probably one using a multiplier phototube; photon noise, including both signal fluctuation and fluctuation in ambient light is therefore the most important noise to be considered. The phototube introduces loss (attenuation) because of its failure to respond to each photon and also introduces additional noise because of its dark current and the fluctuation in output pulse energy for each detected photon, although these sources of noise are probably negligible. Evaluation of the information efficiency or capacity of sample systems appears to be the next step, although the theory of the noise properties of an actual laser should be investigated first to permit analysis of all important types of systems. A preliminary calculation indicates that if T/ξ is equal to two, in some cases the information efficiency may be approximately halved. Fully degenerate or internally controlled lasers have not been studied even approximately.

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5.0 MODULATION AND DE-MODULATION TECHNIQUES

The following section considers the virtues and limitations of various carrier modulation techniques, the types, applicability and efficiencies of the methods of source coding, and the limitations imposed on transmission rates imposed by computer storage on burst modulation schemes.

5.1 CARRIER MODULATION TECHNIQUES

As has already been pointed out in the Study Proposal, a fairly large number of modulation techniques have been proposed. These techniques may be classified as being either internal or external depending on whether the laser output is varied within the laser itself or in a separate stage following the laser oscillation. Before attempting a preliminary evaluation of the various methods it is useful to present some general comments regarding internal and external modulation.

In internal modulation the effect is enhanced by the Q of the laser cavity so that primary power requirements are generally smaller. Moreover, there is no loss of laser signal already generated as is inevitable when the light intensity is varied external to the laser. Thus the overall system efficiency could be expected to be greater. Most of the present day problems stem from the relative newness of the laser devices. Thus, for example, gas lasers must operate with a high Q optical cavity and attempts to introduce a modulation element into this cavity can easily quench the oscillations altogether. In addition investigators are still searching for means to improve the frequency and amplitude stability of the laser, and thus it is natural that the various problems be separated and more emphasis be placed on external modulation techniques. As laser technology is improved it is expected that more and more of the research and development will center about internal modulation techniques. Nevertheless, two distinct disadvantages of internal modulation should be recognized. First, most of the techniques result in a non-linear response of the level of oscillation with changes on cavity parameters. More seriously, the bandwidth is limited by the high Q of the optical cavity. To gain an appreciation of this problem consider the path of the average photon in a gas laser. Assuming 99 percent reflection by the output end mirror (and 100 percent reflection at the other end of the cavity), the average photon makes 100 round trips within the laser cavity before being omitted. If this cavity is 1.5 meter long, the photon requires 1 μ sec to escape. Thus the modulation rate must be limited to less than a megacycle. Clearly, for a given gain per unit length of the laser material, a tradeoff exists between bandwidth and output power.

The properties generally descriptive of external modulation are just the reverse of those attributable to internal modulation. Larger bandwidths and more linear responses are to be expected at the cost of low efficiency.

The comparison is particularly apt when a particular effect is utilized to modulate the laser beam either internally or externally. With the above stated characteristics in mind a preliminary evaluation of these modulation methods which have been investigated to date can be made.

1) Pump power modulation

On December 27, 1962, a voice message was transmitted over a distance of 17 miles between the Hughes Baldwin Hills Test Site and the Malibu Research Labs. The transmitter was a He-Ne gas laser modulated by imposing a voice amplitude modulation onto the 28 mc transmitter used to pump the laser. The quality of the voice was quite good despite the presence of a fairly large noise level at the receiver. (The S/N ratio as measured with a narrow band 1 kc amplifier was 15 db). This experiment demonstrates the simplicity and utility of this modulation technique at least for voice communications. The operation can be described by referring to Figure 5.1. The audio signal is superimposed on the 28 mc signal whose level is set between the laser threshold level and its peak output. Clearly, it is undesirable to have 100 percent modulation of the 28 mc signal. Preliminary data indicate that a drive level of approximately 40 watts and a 20 percent modulation leads to acceptable distortion levels. The percent of laser modulation is of course much higher, but further evaluation is necessary before firm figures can be stated. It is also not definitely known as yet what the frequency limitation might be. It is possible that ionization times may play a part so as to limit the frequency response below that of the oscillation build up time ($\sim 1\ \mu$ sec). Improvements on the 28 mc transmitter circuits and broad banding of the matching network is necessary before any final evaluation can be made. In any case, weight and power requirements of the modulation method is small compared to that of the basic laser.

Pump power modulation in the case of the semiconductor lasers is expected to allow much wider bandwidths. Ga-As diodes, when emitting incoherently, have already been used to transmit television signals (See Ref. 1). Since the pumping method is more direct in this case (i.e., population inversion is achieved by injecting holes into the N region of a PN junction) larger percent modulation should be possible before incurring appreciable distortion. Limitations imposed by the junction capacitance would undoubtedly lead to a tradeoff between power output and bandwidth. Again, the modulation power requirements should be small compared to the primary laser power requirements.

The hair-trigger mode (Ref. 2) of modulation clearly falls within the realm of pump modulation. Unlike the previous schemes which could be adapted to either analog or digital modulation, the hair-trigger mode would be limited strictly to some form of pulse modulation (either PM or PPM). Again, power requirements should be relatively small.

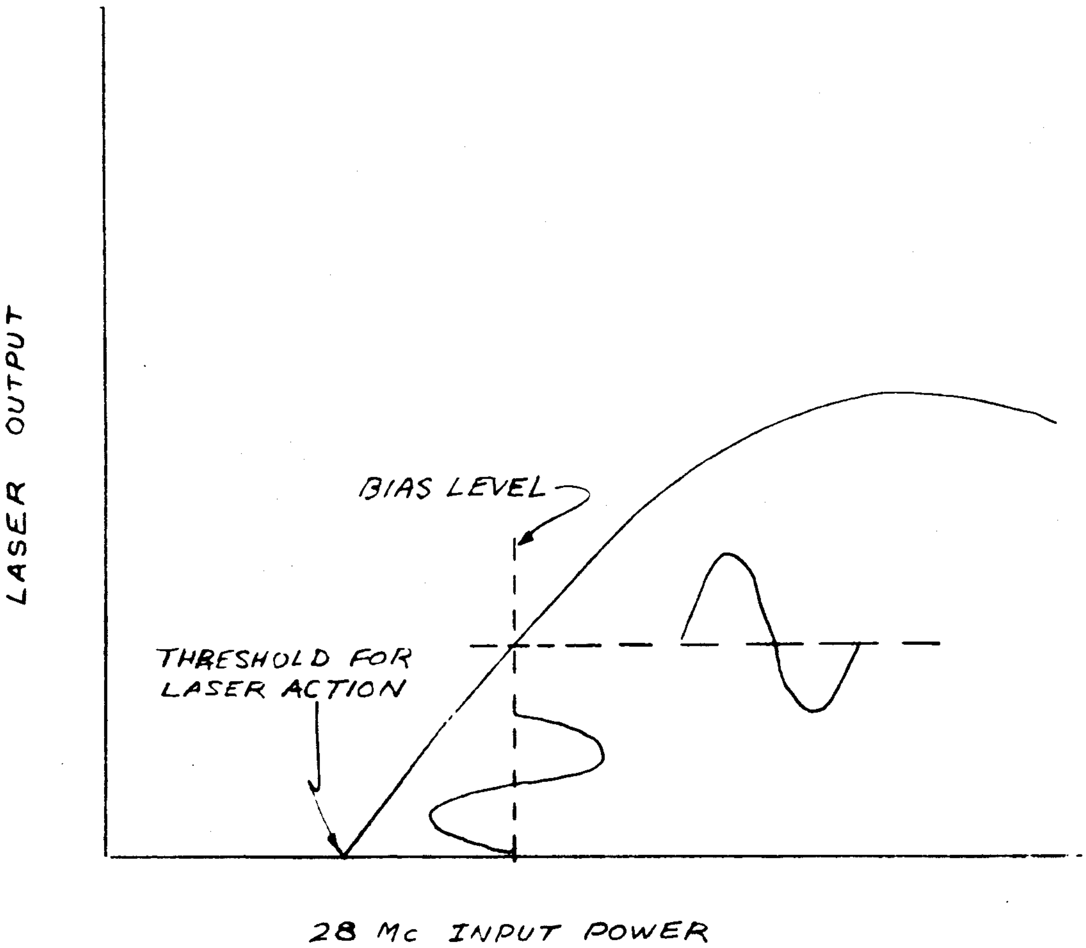


FIGURE 5-1 PUMP MODULATION IN GAS LASER

2) Pockel Effect Modulators

The most widely investigated modulation technique in the laser industry is one which uses the Pockel effect. Significant advances have been recorded within the past year which have resulted in wide bandwidths and decreased power requirement. Either intensity or phase modulation may be obtained depending upon whether an analyzer polarization filter is used.

Crystals which may be used on Pockel modulators include various dihydogen photphates, $Z_{M2}Ce$ (Sphalerite), and CuCl (suprous chloride). The latter has the highest electro-optical of all known crystals. (Ref. 3) In addition the crystal has cubic symmetry and therefore exhibits less light leak than the dihydogen phosphates. Perhaps the most advanced modulator reported so far (Ref. 4) is one employing a traveling wave structure consisting of a parallel plate transmission line in which a portion of the dilectric is ADP or KDP with the optic axis perpendicular to the direction of the light beam. The device exhibits a gigacycle bandwidth and requires only 12 watts of microwave power for 100 percent modulation. Further developments in this rapidly advancing field should see a further improvement in Pockel effect modulators allowing external modulation of either intensity or phase to be accomplished within reasonably sized packages. Primary power requirement of less than 50 watts with an overall weight of 20 pounds would seem to be a reasonable objective.

A promising application of a Pockel or Kerr cell for modulating a ruby laser involves their use in regeneration control after smoothing the laser output with a feed-back circuit. A block diagram of this scheme is presented in Figure 5.2. The use of the feed-back loop to change the laser output from a series of pulselets to a smooth pulse has already been demonstrated (Ref. 5). By modulating the bias on the Kerr Cell it should be possible to obtain modulation rates well in excess of 10 mc during the pulse duration.

Another approach would dispense with the feed-back loop but would use the periodicities of the pulselets themselves as a basis for the modulation. The control of the relaxation time constant either with a Kerr Cell, or perhaps with small changes in pump level, would then yield a form of pulse position modulation in which the position of each pulselet relative to the previous pulselet would convey the information. It is forseen, however, that this method may be extremely sensitive to heating within the ruby and further investigation is necessary to determine its feasibility.

3) Other modulation techniques

Modulation techniques utilizing mechanisms other than pump power variation or the Pockel effect are probably less attractive. Either the power requirement is too high or the frequency response is sharply limited. A final evaluation will be made at a later date. The effects which have been utilized include ultrasonic pressure (Ref. 6) and magnetostricture systems (Ref. 7). Little if any experimental data is available concerning modulators utilizing Zeeman or Stark effects, or employing double resonance techniques to effect direct modulation of the laser level populations.

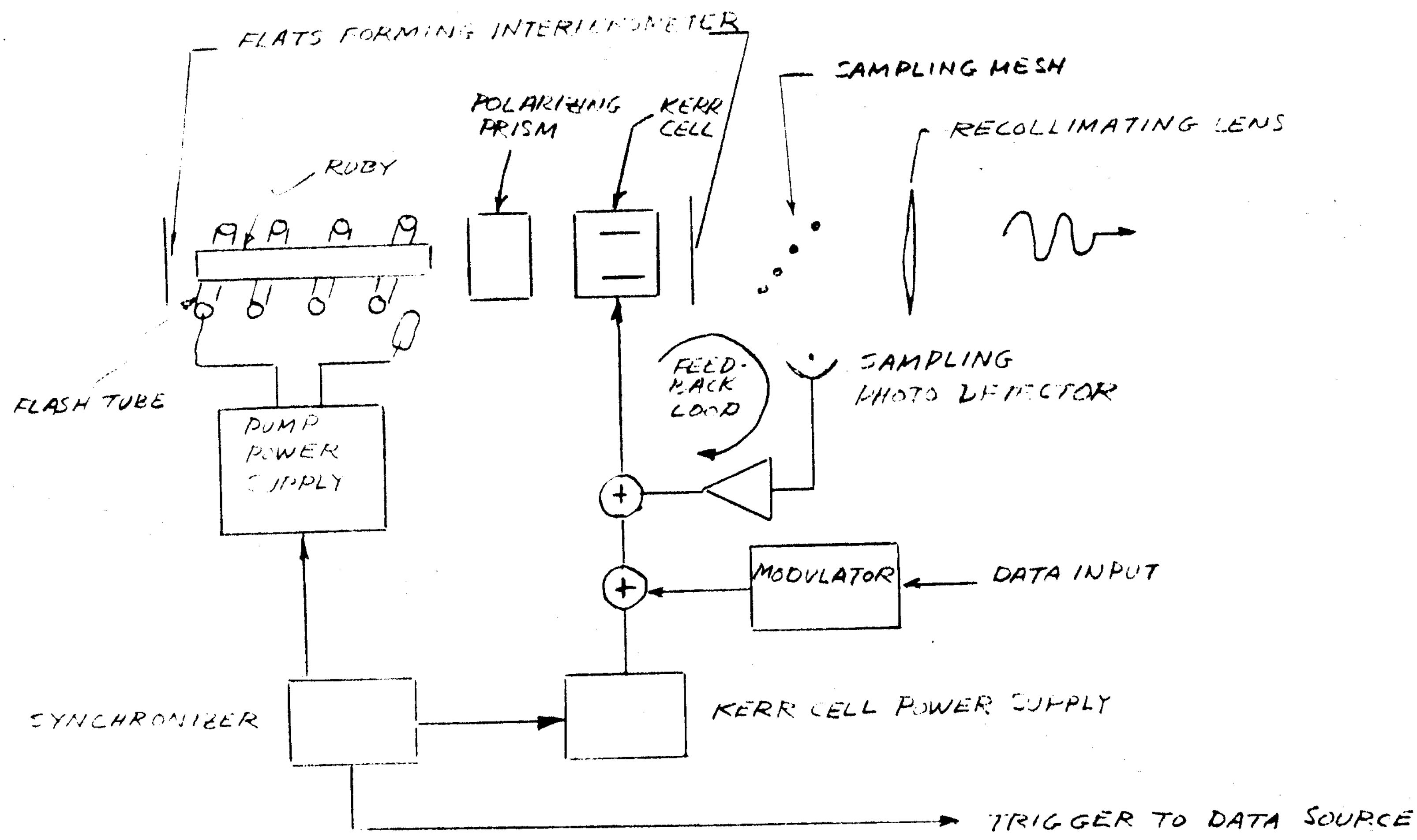


FIGURE 5-2 LASER TRANSMITTER WITH FEEDBACK SMOOTHING LOOP

5.2 CARRIER DEMODULATION TECHNIQUES

An overall evaluation of light detection devices for optical communications may be made on the basis of sensitivity, spectral response, and response time. The various types available include thermal, photomultipliers, traveling wave phototubes, PN junctions, and photoconductors. Thermal detectors exhibit a flat uniform response throughout the optical and IR spectrum and have fair sensitivity. However, the response time is greater than 1 milli-sec so that they must be ruled out in most instances. Photo multipliers and traveling wave phototubes have excellent sensitivity in the visible region of the spectrum and can be made with a large detector area. The power drain is small but high voltage supplies are required. The frequency response can be extended into the microwave region for both the photo multiplier (Ref. 8) or photodiode, but generally the traveling wave phototube will be necessary to demodulate very broadband signals (Ref. 9). At wavelengths longer than 1.2 μ, pn-junction devices must be relied upon as high frequency response is necessary (Ref. 10). Unfortunately, the detection area is quite small so that optical alignment can become a severe problem. Photoconductors have a larger surface area but a much slower response time (>0.1 μ sec.).

Most of the above mentioned detectors can act only as demodulators for an intensity modulated signal. Figure 5.3 shows the phototube used as a demodulator for frequency modulated coherent light (Ref. 11). The dispersing prism converts the FM to ray-angle modulation and hence position modulation on the photo-cathode. The resulting modulation of the electron beam gives rise to the excitation of a transverse wave which can be appropriately amplified and detected.

Although light detectors capable of microwave response exist, they are still in a state of early development. Furthermore, there is a severe lack of large surface, fast detectors in the infrared region. A heterodyne system has been proposed (Ref. 12) which would permit shifting subcarrier modulation down from the microwave range before detection and thus permit the use of detectors which operate only up to VHF. Figure 5.4 shows a block diagram of the heterodyne demodulation of an intensity modulated beam. Many channels of information could be carried on a single light beam if multiplex techniques were used in conjunction with the heterodyne system.

5.3 GENERAL DATA MODULATION TECHNIQUES

The many modulation methods of representing data breakdown into three essential forms. The first type transforms a source signal waveform into a continuously variable modulation parameter. A second technique involves time quantitization with continuous modulation parameters. The third type is characterized by quantizing time and allowing the source signal to take on only a discrete set of possible values.

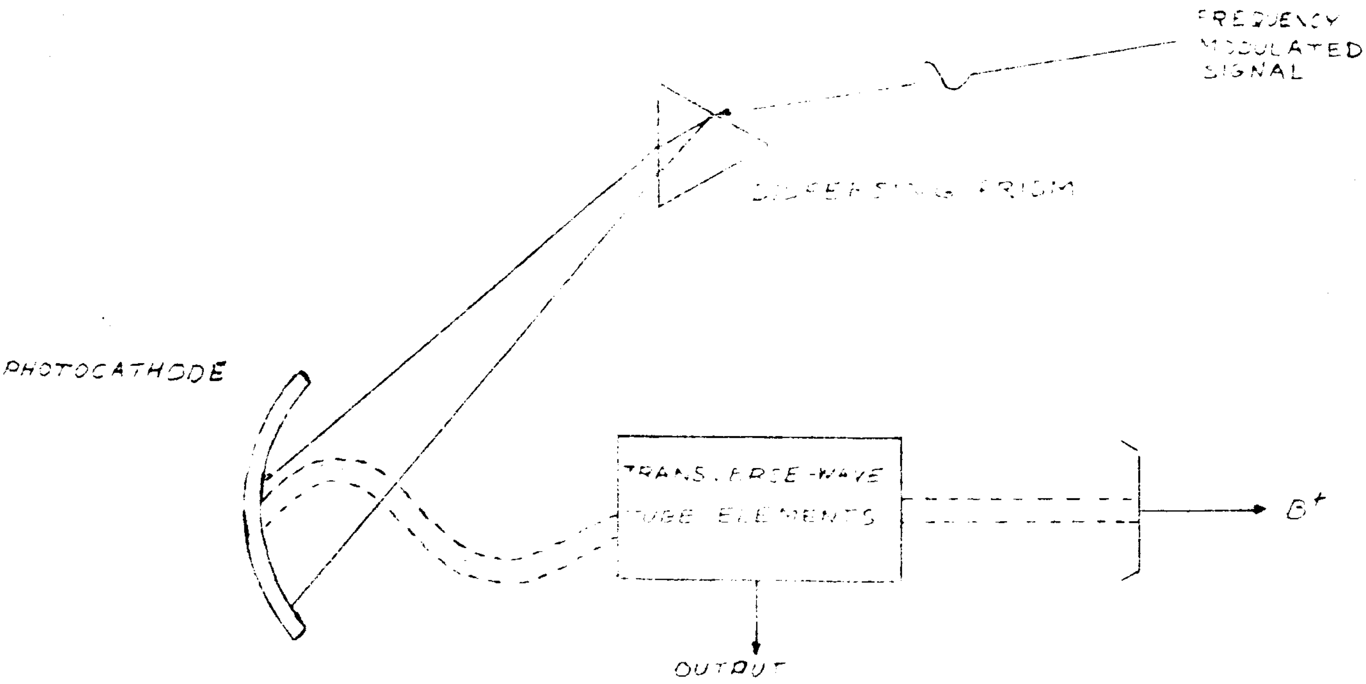


FIGURE 5-3 MICROWAVE [illegible] PHOTOTUBE FOR DEMODULATING COHERENT LIGHT

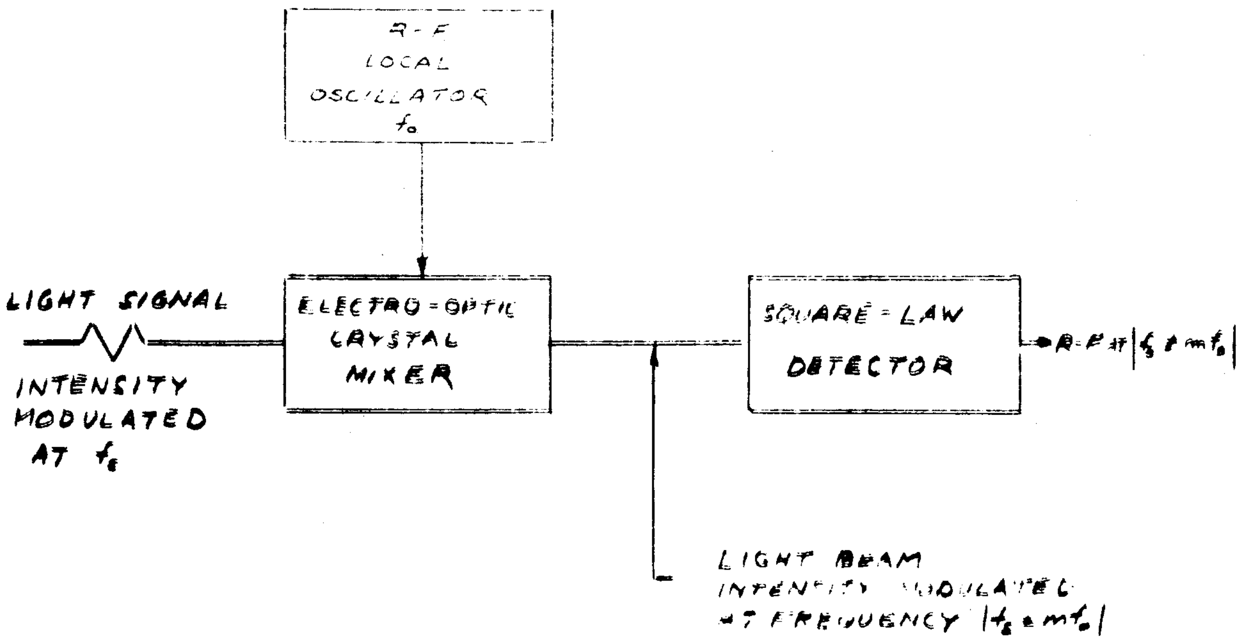


FIGURE 5-4 HETERODYNE LIGHT RECEIVER [illegible] NARROW BAND DETECTORS

DATA MODULATION TECHNIQUES

	Type I	Type II	Type III
Time	Continuous	Quantized	Quantized
Modulation Parameter (Amplitude, Frequency, Phase, Etc.)	Continuous	Continuous	Quantized
Examples	FM, AM	PAM, PFM	PCM

The Type II and Type III modulation techniques provide a greater amount of system flexibility than the Type I techniques since time multiplexing will allow the simultaneous transmission of data from several sources. The Type III systems offer the advantage that data is in a form suitable for automatic data processing.

1) Type I Modulation Systems

With Type I Systems the parameters of a sinusoidol carrier waveform are varied in accordance with the information being transmitted. Frequency division multiplexing in which frequency separated modulated subcarriers are added together to modulate the carrier is possible with Type I systems. However, its use provides a relatively small number of communication channels because of the equipment complexity involved in providing negligible channel cross-talk and good communication efficiency for large numbers of channels. Frequency multiplexing also does not provide the space data link user with equipment which is easily modifiable to efficiently allow for changes in subcarrier channel bandwidths and number of signal channels.

2) Type II Modulation Systems

Th Type II systems a sample from a signal source is used to modulate a carrier waveform for the sample period. The carrier parameters for Type II systems are not limited to the frequency, phase, and amplitude parameters of Type I systems, but may utilize other variables such as pulse position or pulse duration. With Type II systems, the carrier waveforms must have the capability of a high signal-to-noise ratio at the receiver and the waveforms must be chosen so that transmitted sample values do not interfere with one another.

3) Type III Modulation Systems

The only difference between Type II and Type III systems is that in the latter the modulation parameter is constrained to a discrete set of values rather than being continuous as is the case with Type II systems. In theory any number of discrete waveforms could be utilized to transmit information, but the only practical system devised is that in which only two waveforms are employed. Such systems that utilize binary waveforms are called pulse code modulation systems.

Digital data transmission is rapidly becoming the standard for space telemetry. The improved efficiency of power and bandwidth utilized per information bit transmitted, the general accuracy, flexibility and reliability are among the reasons accounting for the wide application of digital techniques.

5.4 LASER SOURCE CODING

The investigation of the physical aspects of laser modulation has shown that phase or frequency modulation has not developed to such an extent that it can be presently considered for a laser communication system. However, improvements in laser modulation technology should provide phase and frequency modulation in the near future. For the present, the designer will have available only techniques of amplitude and pulse modulation.

Table 5.1 illustrates the present possible laser modulation methods. In the case of laser amplitude modulation, analog data can be represented in standard A M form for carrier modulation or in amplitude or angle form with subcarriers. Digital data in pulse code modulation form can be used to amplitude modulate the carrier or subcarrier. In addition, the PCM data can be placed in a frequency shift keying or phase shift keying mode on the subcarrier.

The pulse modulation methods can be categorized into three types for analog data-pulse amplitude modulation, pulse duration modulation, and pulse position modulation. For digital data in PCM form, the same three carrier modulation methods are employed.

With the choices of modulation methods given in Table 5.1, the selection of the "best" modulation method for a communication system is essentially a selection of the modulation method that can provide the highest fidelity of transmission for a given transmission power and rate. This selection must, of course, be made under the restrictions of the complexity of the modulation and demodulation equipment. In order to evaluate the various modulation systems, the characteristics of the channel must be specified. If the channel disturbances can be represented by White Gaussian noise, a comparison of the modulation systems can be readily made.

The transmission of data in digital form offers a substantial increase in the transmission fidelity. With a digital data system and amplitude modulation the choice of modulation is between amplitude, frequency, and phase modulation using subcarrier techniques. Of the three possibilities phase shift keying of the subcarrier provides the minimum probability of transmission error. For the pulse modulation methods PPM results in the smallest error probability. For typical systems the signal-to-noise ratio of a PPM system will be about 10 db higher than that of a comparable PAM system.

TABLE 5.1 - PRESENT POSSIBLE LASER MODULATION METHODS

AMPLITUDE MODULATION METHODS

Data	Carrier Modulation	Subcarrier Modulation
Analog	AM	AM/AM FM/AM PM/AM
Digital	PCM/AM	PCM/AM/AM PCM/FSK/AM PCM/PSK/AM

PULSE MODULATION METHODS

Data	Carrier Modulation
Analog	PAM PDM PPM
Digital	PCM/PAM PCM/PDM PCM/PPM

5.5 DATA STORAGE LIMITATIONS ON TECHNIQUES

Many layman's (and scientific) articles make claims like "the entire bible can be transmitted in a fraction of a second on a single laser burst." In general such claims are false not so much from deficiencies of lasers, but from the physical limitations of the peripheral equipment of a laser communication system.

If a laser burst system with one millisecond bursts at a one second repetition rate is postulated for one frame per second TV, each burst would have to carry 1.25×10^6 bits of information in a fine bit PCM code. The modulation bandwidth for this amount of data is well within the limitations of the laser. However, for this system the data would have to be collected and stored in the transmitter dead time of nearly one second and then removed from storage and transmitted in one millisecond. At the receiver the collection and storage time would again be one millisecond. The storage rate for such an operation of 1.25×10^9 bits/sec. is well beyond the state-of-the-art for storage media. Figure 5.5, due to Rajchman (Ref. 13), illustrates the limits of capacity for feasible storage systems. The example storage requirements are indicated by cross.

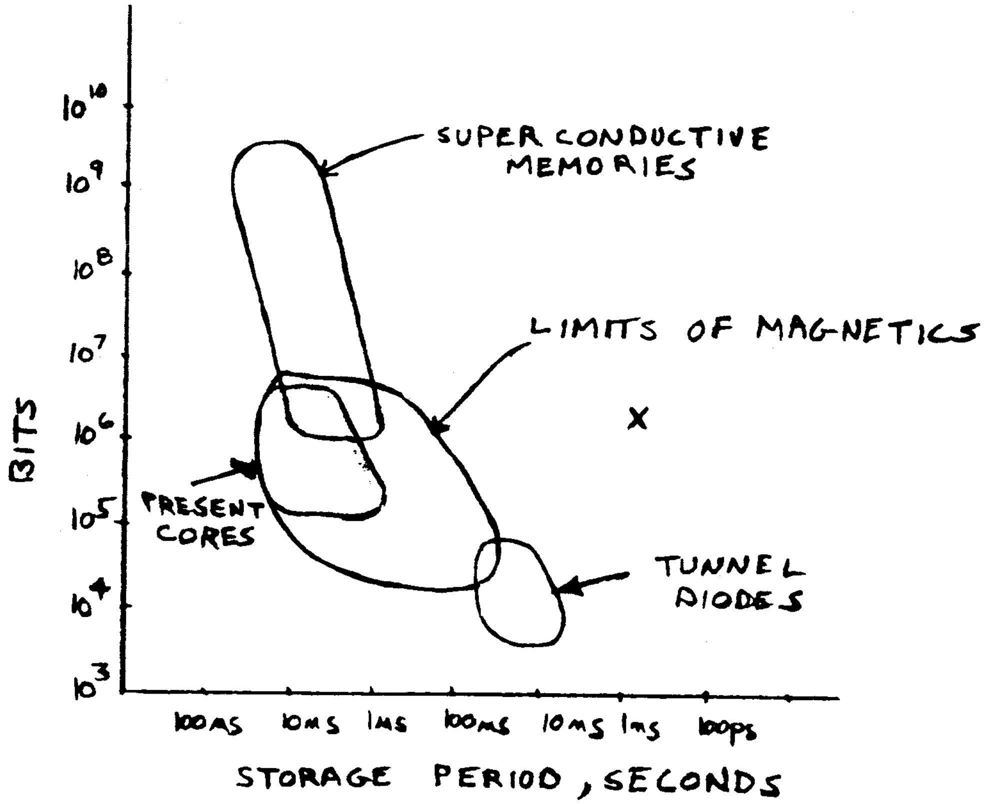
The question then arises as to what is a feasible limit for the amount of information carried in a laser pulse that can be stored by a presently available storage unit. From Figure 5.5 it can be seen that the maximum storage rate per bit will be 0.8 μs for 10^5 bits for a core memory. For a millisec. laser burst the number of information bits, N, will be

$$N = \frac{10^{-3} \text{ sec.}}{0.8 \times 10^{-6} \text{ sec./bit}} = 1{,}250 \text{ bits}$$

With a 50 nano-second tunnel diode memory the situation is somewhat improved. In this case N will be

$$N = \frac{10^{-3} \text{ sec.}}{50 \times 10^{-9} \text{ sec./bit}} = 20{,}000 \text{ bits}$$

The information rates that have been computed can be referenced to the typical data rate requirements given in the Systems and Operations Analysis Section.



LIMITS OF STORAGE CAPACITY
FIGURE 5-5

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